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YUCCA MOUNTAIN SITE CHARACTERIZATION PROJECT

RADIOLOGICAL PROGRAMS

AMBIENT RADON AT THE YUCCA MOUNTAIN SITE

(SCPB: N/A)

REV. 00

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DISCLAIMER

EXECUTIVE SUMMARY

This report summarizes the results of the ambient radon monitoring activities conducted by the Radiological/Environmental Field Programs Department of the Civilian Radioactive Waste Management and Operating Contractor (CRWMS M&O), Yucca Mountain Site Characterization Office.

Overall, outdoor radon concentrations measured at the Yucca Mountain site were within the range of those reported for other areas in Nevada and the continental United States. Though there was some evidence of trends with time at some monitoring sites, regional atmospheric radon concentrations to date, do not appear to have changed significantly since the inception of site characterization activities. A preliminary dose assessment yielded an estimated annual effective dose equivalent of 134 mrem based on a continuous exposure to the average ambient radon concentration measured at the Yucca Mountain site.

Concentrations were measured using two types of systems, passive electret ion chambers (EIC) and continuous radon monitors (CRM). The EICs produced time-averaged radon concentration data and the CRMs were used to study radon fluctuations over time. Between 1991 and 1995, the mean radon concentration at the site, as measured by EICs placed one meter above ground level, was 0.32 ± 0.15 pCi L^{-1}. Radon concentrations varied between monitoring locations and between years. Station NF38, located near the North Portal of the Exploratory Studies Facility (ESF), exhibited the highest overall average radon concentration at 0.55 pCi L^{-1} (1992 to 1995). Concentrations appear to cycle diurnally, generally peaking in the early morning hours and being lowest in the afternoon. The data also suggested that radon concentrations may fluctuate seasonally.

The work accomplished between 1991 and 1995, established radon levels in the general area surrounding Yucca Mountain. It is recommended that further work focus directly on those locations that have the greatest potential for influencing ambient radon levels, in particular, the north and south portals of the ESF. In addition, it is recommended that further analyses be conducted on the relationship between radon and the site-specific environmental factors that affect radon levels, fluctuations and trends.

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1.0 INTRODUCTION

This report summarizes the results of ambient radon monitoring activities performed from 1991 through 1995 by the Radiological/Environmental Field Programs Department (R/EFPD) of the Civilian Radioactive Waste Management System Management and Operating Contractor (CRWMS M&O), Yucca Mountain Site Characterization Office.

Ambient radon monitoring was initiated in June 1991 as part of a radiological monitoring program designed to determine existing levels of ambient radiation and radionuclide concentrations in the environs of the proposed repository site. The controlling document for all YMP radiological monitoring activities conducted by R/EFPD is the Radiological Monitoring Plan (DOE 1988, 1990). Monitoring activities are carried out in accordance with the Site Investigation Package for Radiological Monitoring (CRWMS 1995).

1.1 BACKGROUND

In 1982, Congress passed and the President signed into law the Nuclear Waste Policy Act (NWPA). This federal law directed the Department of Energy (DOE) Office of Civilian Radioactive Waste Management to initiate efforts to develop the nation's first mined geologic disposal facility for high-level radioactive waste. The national issue of disposal and permanent storage of nuclear wastes was addressed in this act, specifically, spent fuel from the nation's nuclear power plants and high-level radioactive waste from the production of defense materials. Also embodied within the law were descriptions of the process for siting, licensing, constructing, operating, closing, and decommissioning a geologic repository. In 1987, the NWPA was amended by Congress, and the DOE was directed to conduct site characterization activities solely at the Yucca Mountain site.

Compliance with the Nuclear Waste Policy Amendments Act (NWPAA) is one of the primary goals of the R/EFPD radiological monitoring activities. Knowledge of the radiological pathways to man within the study area is essential in adhering to federal standards.

1.2 SITE DESCRIPTION

The YMP site is located approximately 160 kilometers (km) northwest of Las Vegas, in Nye County, Nevada. The site, located on the northern edge of the Mojave Desert, is characterized by a series of arid, linear mountain ranges and valleys. The location of the proposed geologic repository is Yucca Mountain, a north-south volcanic ridge (maximum elevation of 1494 meters[m]) which slopes steeply to the west into Crater Flat (elevation 1189 m) and east to Jackass Flats (elevation 1097 m). A more detailed description of the site's biological, meteorological, geological and cultural features can be found in the YMP Environmental Assessment (DOE 1986) and the Annual Site Environmental Reports (DOE 1993, 1994, 1995).

1.3 SOURCES AND PROPERTIES OF RADON

Radon makes up the largest percentage of the annual average effective dose equivalent delivered to the U.S. public from background radiation. The National Council on Radiation Protection and Measurements (NCRP) estimated that amongst the 360 millirems (mrem) dose from background radiation (all sources), 200 mrem (55%) is from radon (NCRP 1987a).

Radon is a naturally occurring, radioactive noble gas. Three isotopes of radon occur in nature, ^{219}Rn (half-life = 4 seconds), ^{220}Rn (half-life = 56 seconds) and ^{222}Rn (half-life = 3.8 days), members of the actinium, thorium and uranium series, respectively. However, in outdoor atmospheric measurements of radon, ^{222}Rn is the most abundant and the most readily detected. The distance traveled by ^{219}Rn and ^{220}Rn before decaying is relatively short because of their short half-lives. In addition, the relative abundance of Uranium-235 (^{235}U), head of the actinium series of which ^{219}Rn is a member, is very low in soil (0.7%). These factors, in combination with the configuration and characteristics of the YMP radon detection systems, result in a low probability of detecting these isotopes in outdoor radon measurements.

The primary source of atmospheric radon (^{222}Rn) is from the decay of radium (^{226}Ra) in rock and soils. Radium-226 is a member of the primordial uranium decay series headed by ^{238}U (Figure 1-1). Varying amounts of ^{238}U and ^{226}Ra are found in most rocks and soils. The concentrations of ^{238}U and ^{226}Ra measured in the soils of Yucca Mountain have been reported in Distribution of Natural and Man-Made Radionuclides in Soil and Biota at Yucca Mountain, Nevada (TRW 1996b). Once generated, ^{222}Rn decays through a series of short-lived radionuclides to ^{210}Pb (half-life = 21 years) and eventually, to stable ^{206}Pb. Radiological risk is associated primarily with the inhalation of the short-lived ^{222}Rn progeny, ^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po. The majority of the dose from radon is delivered to the bronchial epithelium from the decay of the alpha-emitting ^{218}Po and ^{214}Po (NCRP 1987a,b).

Several different physical and meteorological factors influence the emanation rate of radon from soil. These critical factors include:

- radon production per unit volume of soil pore space
- soil porosity and permeability
- sources that cause changes in pressure gradients above or below ambient atmospheric pressure.

Once in the atmosphere, transport of radon is controlled primarily by turbulent diffusion and vertical components of wind (NCRP 1988). A comprehensive discussion of radon transport mechanisms can be found in Tanner (1964, 1980).

Typically, average outdoor radon concentrations in the United States range of 0.1 to 0.5 pCi L^{-1} (Eisenbud 1987, Gessel 1983). This report summarizes the results of outdoor radon measurements taken between 1991 and 1995 in the environs of Yucca Mountain. A report summarizing the ESF radon monitoring results is currently being prepared.

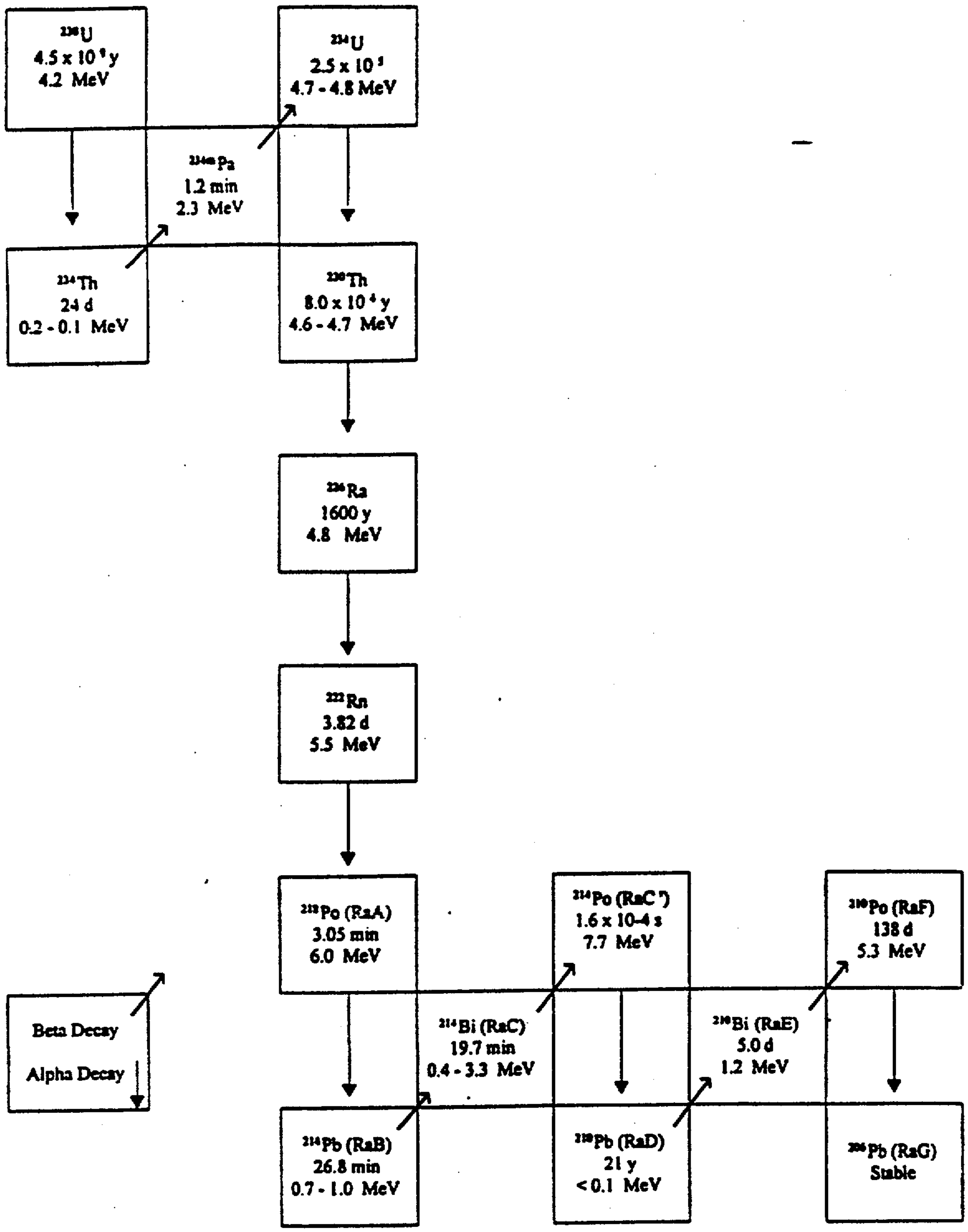


Fig. 1-1 Principal decay scheme of the uranium series.

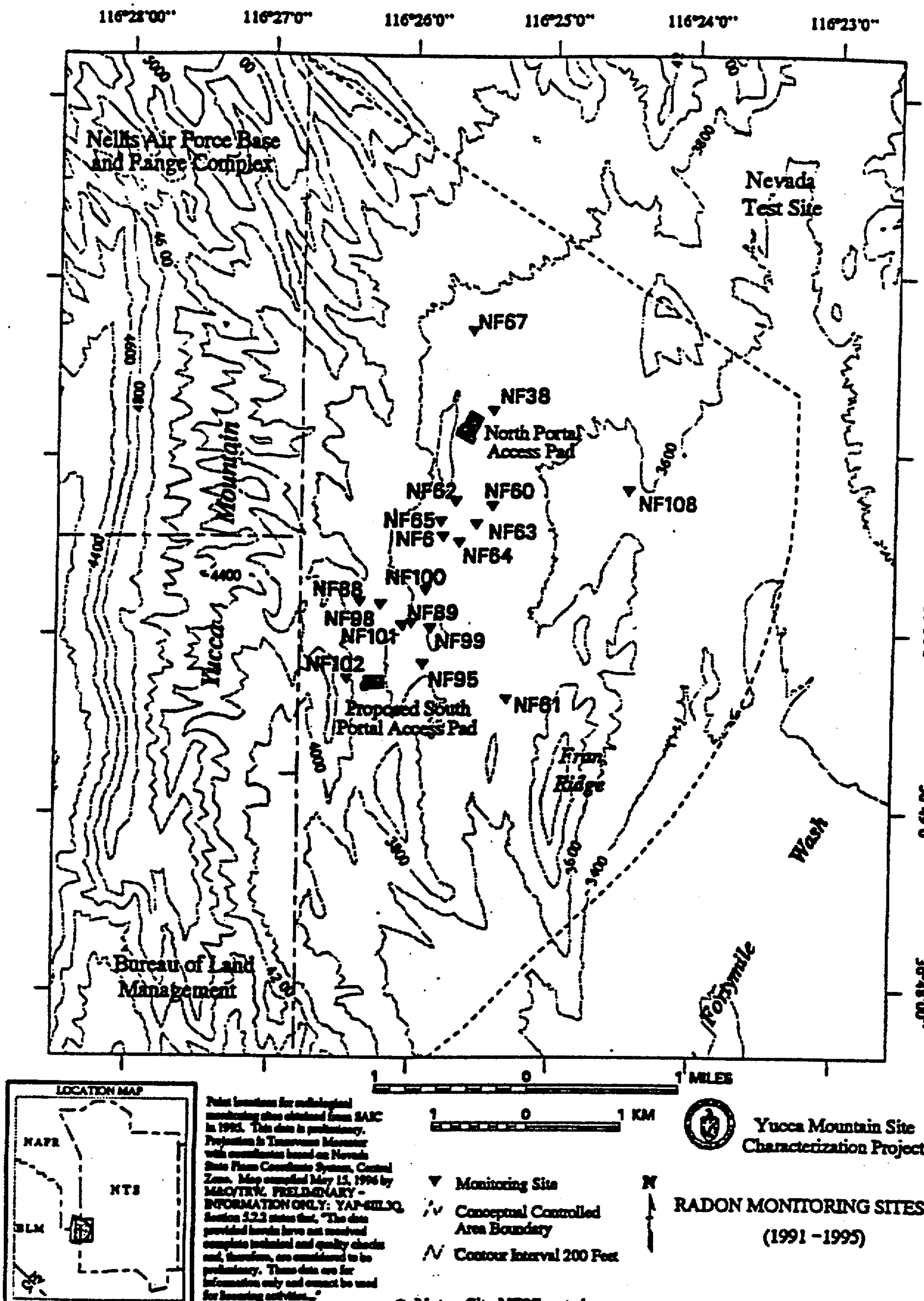
2.0 AMBIENT RADON MONITORING METHODS

2.1 SAMPLING LOCATIONS

Radon monitoring activities were initiated at the Yucca Mountain site in June 1991. Between 1991 and 1995, radon data were collected from 19 on-site locations. Eighteen of the 19 stations were located within a 3.2 km radius of the north portal of the ESF (Figure 2-1). Station NF87 is located approximately 13.5 km southeast of the ESF North Portal in the field operations support area. On-site locations are collectively referred to as near-field (NF) stations.

In October 1992, a radon monitoring station (FF83) was established on the campus of the University of Nevada, Las Vegas (UNLV). Maintained by the UNLV Health Physics Program, this station remained in operation until October 31, 1994, when a new station (FF12) was established on the campus. Station (FF12) remained in operation until June 1995. The stations on the UNLV campus are collectively referred to as far-field (FF) stations. Table 2-1 includes the reasoning behind the initial siting of a station. The dates individual stations were established are given in Table B-1 in Appendix B.

At all stations, near-field and far-field, passive electret ion chambers (EIC) were deployed to measure time-averaged radon concentrations. In addition, to study how radon concentrations fluctuate with time, continuous radon monitors (CRM) were set up at two of the near-field stations. Each system is described in the following sections.



RADON MONITORING SITES (1991 - 1995)

* Note: Site NF87 not shown on map

YMP-96-078.0

Table 2-1. Initial YMP radon monitoring station siting rationale.

Location	Reason For Deployment
NF06, NF38, NF67, NF102, NF108	Monitor Exploratory Studies Facility, North and South Portals
NF60, NF61, NF62, NF63, NF64, NF65	Monitor proposed surface facilities area
NF87	Monitor Field Operations Center (FOC) environs
NF88, NF89, NF95, NF98, NF99, NF100, NF101	Monitor proposed muck and topsoil storage areas
FF12, FF83	Monitor nearest urban area

2.2 PASSIVE ELECTRET ION CHAMBERS (EIC)

The EIC system consists of an ionization chamber coupled to a positively charged Teflon™ electret. Radon gas diffuses into the chamber through a filter. As the radon in the chamber decays, the chamber air is ionized. The negatively charged ions are attracted to the positively charged electret, and the electret is partially discharged. The change in electret voltage is proportional to the radon concentration and exposure time (Rad Elec Inc. 1991). A discussion of the computational methods used to calculate radon concentration using EICs is given in Appendix A.

All EICs were placed approximately one meter above ground level (AGL). Typical exposure times ranged from 28 to 33 days. Initially, EICs were deployed in the open without shelter from environmental elements. To protect the systems and minimize data losses, open-air environmental shelters were installed at the sites in June 1992.

Quality control measures employed included routine reading of standard reference electrets of known voltage and the use of closed controls to check for excessive electret electronic drift. In addition, duplicate measurements were made at each site.

2.3 CONTINUOUS RADON MONITORING (CRM)

In June 1993, CRMs were installed at near-field stations NF06 and NF87. Station NF06 is situated at a height of approximately 3 m AGL, with NF87 at approximately 2 m AGL. Radon concentrations initially were measured in 10-minute intervals; however in July 1994, the sampling interval was changed to 60 minutes to improve counting statistics.

CRM systems operate by continuously pumping filtered air though an 18.5 L (nominal) electrostatic chamber at 0.5 L min^{-1}. As radon decays in the chamber, the positively charged progeny are attracted to a cathode overlaying an alpha-particle sensitive scintillator. A light pulse is produced as alpha-particles, from the decay of ^{218}Po and ^{214}Po, strike the scintillator. The light pulses are transmitted, via a light pipe, to a photomultiplier tube where they are amplified and converted to an electrical signal. The signal is sent to a scaler and a count is recorded. The number of light pulses counted is proportional to the concentration of radon in the chamber (Pylon 1992).

2.4 DATA ANALYSIS

Data distributions were tested for normality using a Kogomorov-Smirnov test (Ott 1988). The null hypothesis is that the data match the expected pattern if they were drawn from a population with a normal distribution. The alternative hypothesis is that the data vary significantly from the pattern expected if the data were drawn from a population with a normal distribution. If the null hypothesis was rejected with a 95% confidence level ($P < 0.05$), the data were considered to have been drawn from a population that was not normally distributed. If the data were not normally distributed, a logarithmic transformation was applied and the data retested for normality. If the transformed data did not appear to fit a normal distribution, non-parametric (distribution-free) procedures were used to make quantitative comparisons.

3.0 AMBIENT RADON AT YUCCA MOUNTAIN

3.1 PASSIVE ELECTRET ION CHAMBER MEASUREMENTS

The overall site average radon concentration measured by EICs, for the period 1991 to 1995, was 0.32 ± 0.15 pCi L^{-1} with a median of 0.29 pCi L^{-1}. The highest site-wide annual concentrations were measured in 1992 and the lowest in 1993 (Table 3-1). A Kruskal-Wallis Analysis of Variance on Ranks (Ott, 1988) indicated that the concentrations in at least one of these years was significantly different ($P < 0.0001$) than the concentrations measured in other years. Table 3-2 shows which years were significantly different from each other. Although statistically significant differences were identified between some annual concentrations, the variability of radon concentrations between years was relatively small (Figure 3-1). Less than 0.2 pCi L^{-1} separated the lowest (0.23 pCi L^{-1}) and highest (0.40 pCi L^{-1}) annual medians.

From 1991 to 1995, individual monthly outdoor radon concentrations, measured with EICs, ranged from below the detection limit of 0.05 pCi L^{-1}, as reported by Hopper et al. (1994), to 0.96 pCi L^{-1}. Plots of individual monthly radon concentrations for each station are shown in Appendix B. Figure 3-2 shows the annual mean and standard deviation for each station from 1991 to 1995.

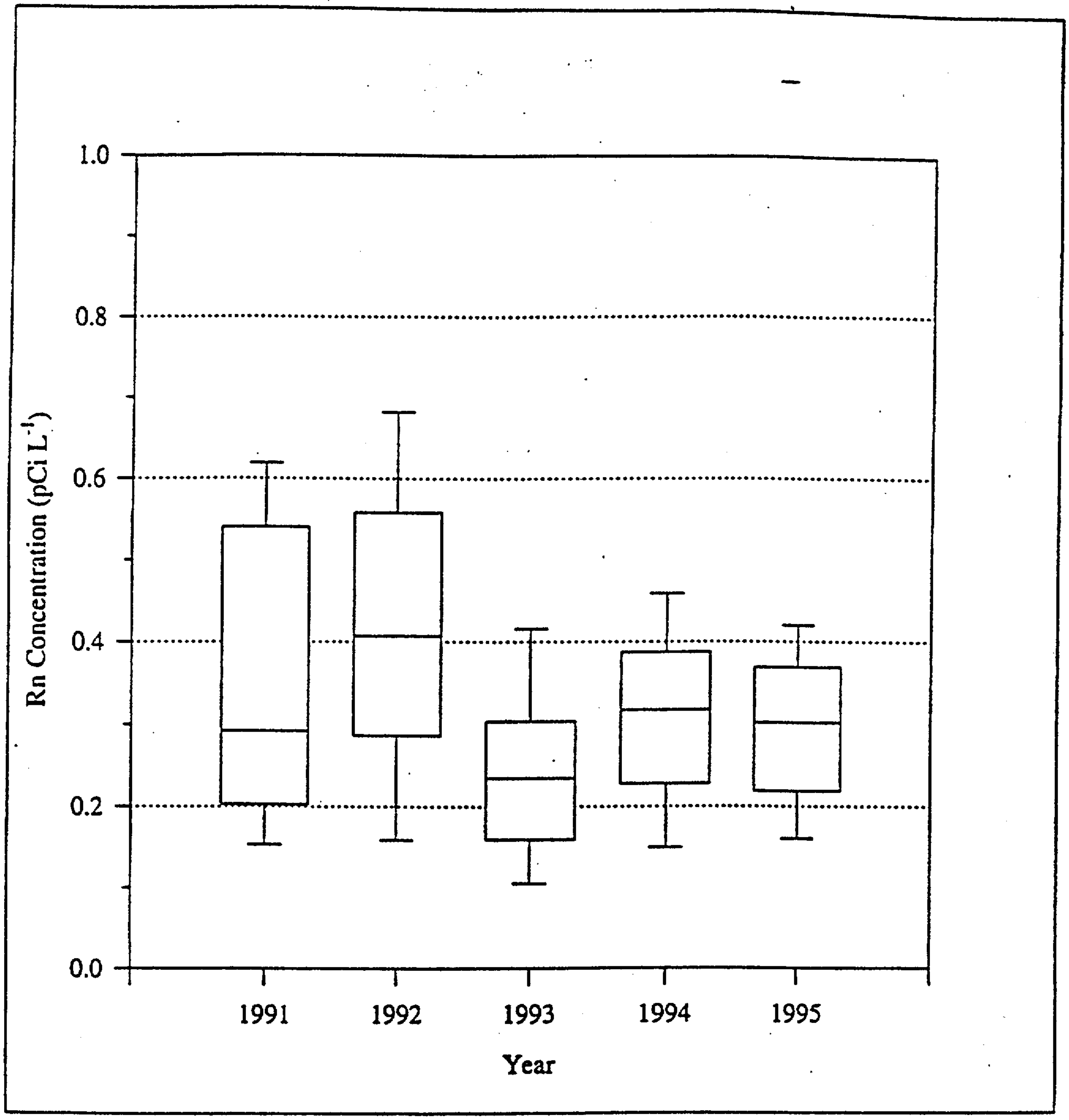
Trends in radon concentration over time at individual monitoring stations were tested using the Mann-Kendall test for trends (Gilbert 1987). At 14 of 20 stations tested, no significant trends were observed. Stations NF99, NF100, NF101 and NF102 showed a significant upward trend. Stations NF65 and NF88 showed a significant downward trend. In all cases, changes over time were relatively slight and further investigation is needed to determine if the trends observed are due to any specific site characterization activities.

	YEAR				
	1991	1992	1993	1994	1995
Mean	0.35	0.42	0.24	0.31	0.31
Standard Deviation	0.19	0.19	0.13	0.11	0.12
Median	0.29	0.40	0.23	0.32	0.30
25th Percentile	0.20	0.29	0.15	0.23	0.23
75th Percentile	0.54	0.56	0.30	0.39	0.38
Maximum	0.79	0.96	0.71	0.68	0.68
Minimum	0.05	0.09	-0.04	0.07	0.02
Number of Samples	59	125	167	174	121

Note: Measurements were made using passive electret ion chambers placed 1 m above ground level.

	1991			
1992		**1992**		
1993	X	X	**1993**	
1994		X	X	**1994**
1995		X	X	

NOTE: Years that were significantly different ($P < 0.05$) from each other are marked with an "X".



NOTE: Horizontal lines (from bottom) represent the 10th, 25th, 50th, 75th and 90th percentiles of the data.

Figure 3-1. Box plots of YMP annual radon concentrations measured using EICs.

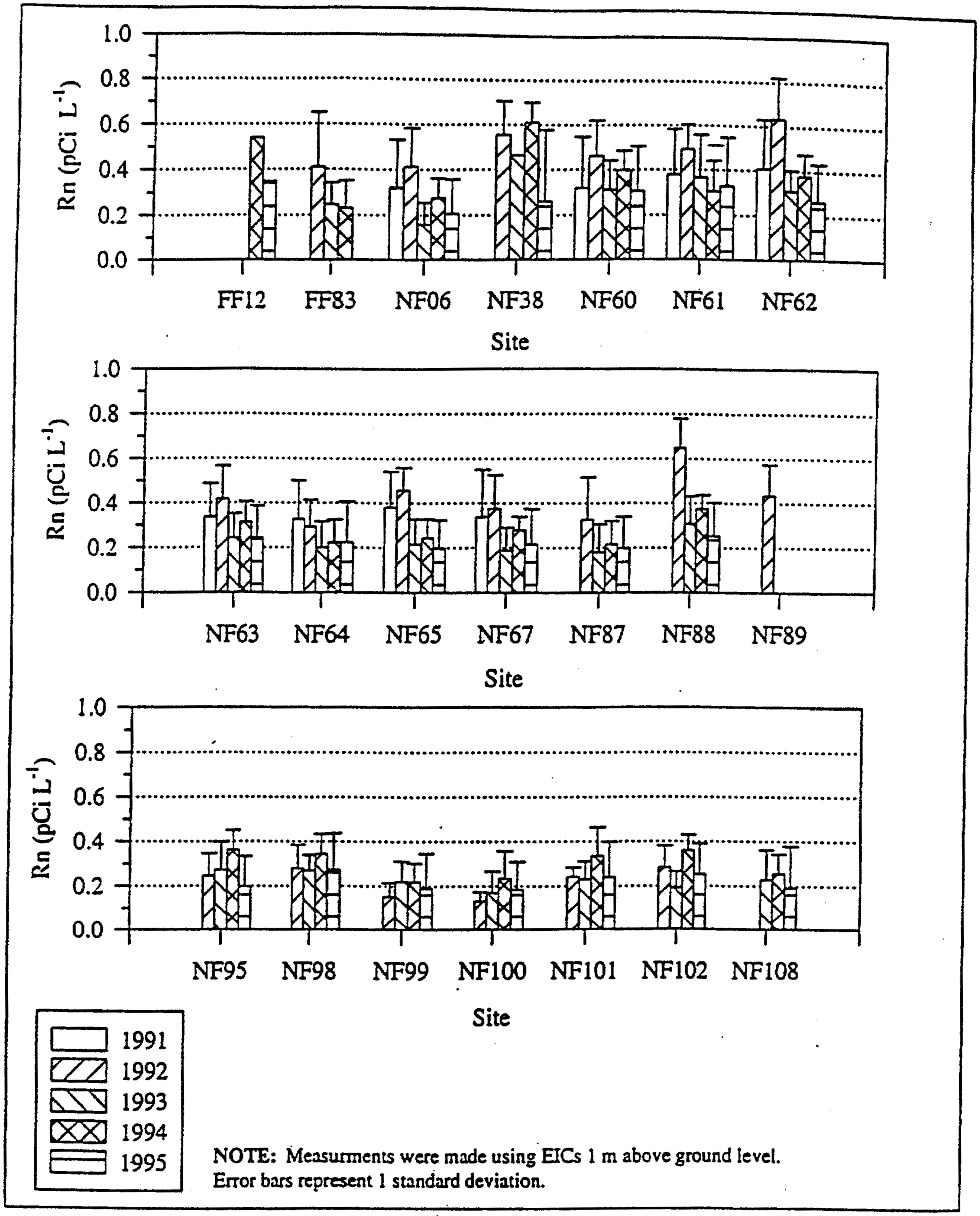


Figure 3-2. Annual average radon concentrations for YMP monitoring sites from 1991 to 1995.

Among the individual stations NF38, the closest station to the North Portal of the ESF, showed the highest overall mean concentration of radon (Table 3-3). However, there is no indication that area radon concentrations have changed significantly since the station was established in 1992. Several months of NF38 data were not used because the coefficient of variation between duplicate measurements exceeded 50%. The station is located near a heavily traveled dirt road leading to the ESF, and it is possible that fugitive dust entered the instrument chamber causing the electret to discharge, resulting in inconsistent readings between the duplicates.

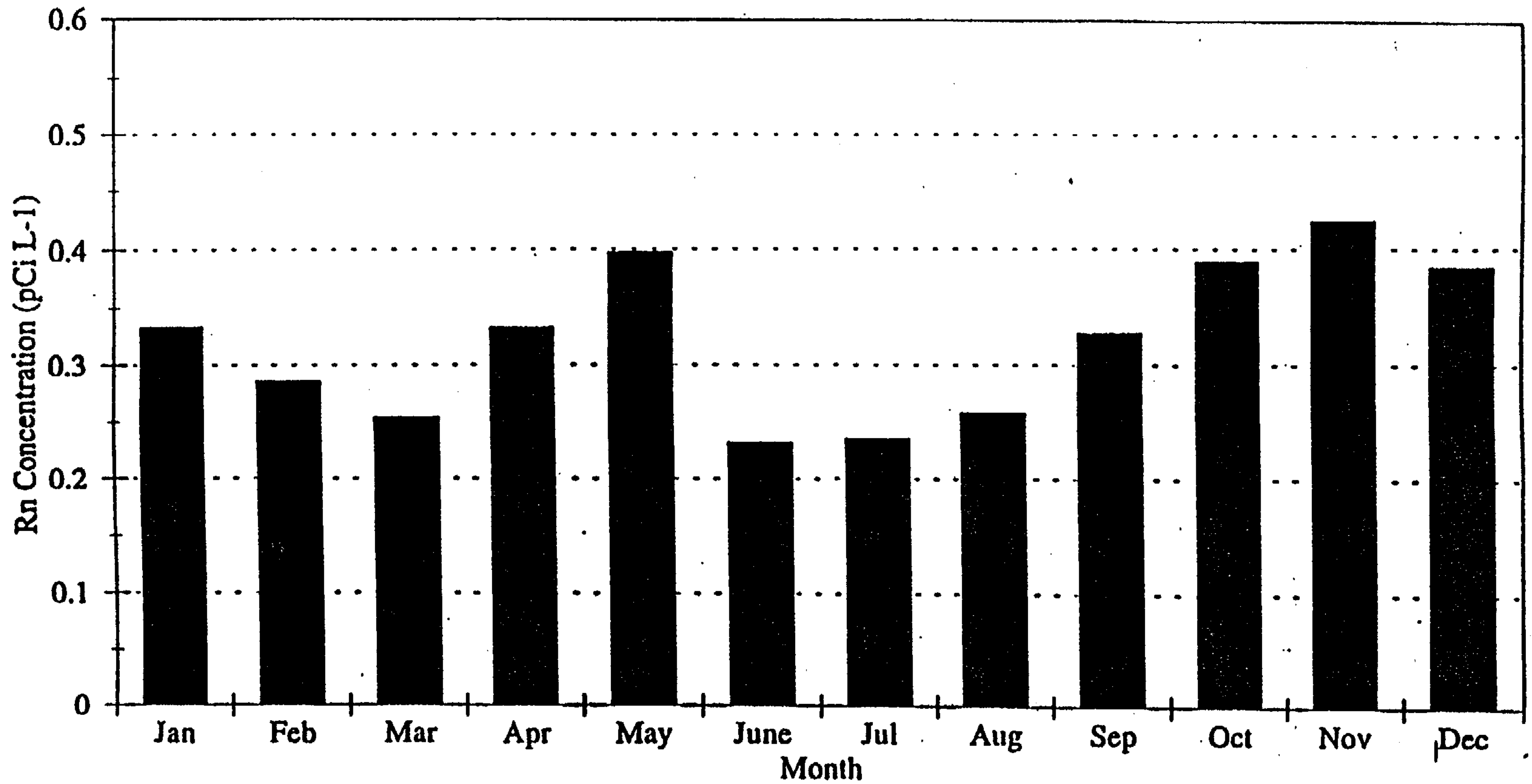
Visual examination graphs of the EIC monthly radon measurements (Figures B-1 through B-21 in Appendix B) showed that several of the stations exhibited a sinusoidal pattern over time, indicating that radon concentrations may fluctuate seasonally. Generally the highest concentrations occurred in the late fall and winter and the lowest concentrations occurred in the summer months . A plot of the monthly averages for the time period 1991 to 1995 shows this trend more clearly (Figure 3-3). Seasonal trends may be the a function of greater atmospheric instability in the summer months . Wind and convection currents caused by heating of the earth surface in summer may increase atmospheric turbulence, thereby increasing vertical mixing of the lower portions of the atmosphere (NCRP 1988, Eisenbud 1987).

Average outdoor radon concentrations in the United States normally range from 0.1 to 0.5 pCi L^{-1} (Gessel 1983). Table 3-4 shows a comparison of the mean outdoor radon concentrations at the Yucca Mountain site with other locations in Nevada and across the United States. All of the studies cited used a measurement system similar to EIC, used in this program. Overall, outdoor radon concentrations measured at the YMP site fall well within the range of concentrations reported for other locations within Nevada and other parts of the USA.

Table 3-3. Radon concentration summary statistics for individual monitoring sites from 1991 to 1995.

Station	Mean	St Dev	Median	10th Percentile	90th Percentile	Max	Min	Count
FF12	0.41	0.12	0.35	0.33	0.54	0.54	0.33	3
FF83	0.27	0.14	0.27	0.13	0.48	0.60	0.11	18
NF06	0.29	0.16	0.27	0.13	0.55	0.69	-0.04	38
NF100	0.20	0.10	0.19	0.08	0.34	0.49	0.04	30
NF101	0.28	0.11	0.26	0.16	0.42	0.51	0.10	31
NF102	0.29	0.10	0.30	0.16	0.39	0.51	0.08	35
NF108	0.25	0.12	0.24	0.10	0.39	0.53	0.06	27
NF38	0.53	0.14	0.55	0.34	0.75	0.75	0.32	15
NF60	0.38	0.15	0.37	0.21	0.58	0.72	0.05	47
NF61	0.40	0.16	0.39	0.20	0.63	0.79	0.17	48
NF62	0.42	0.18	0.40	0.24	0.71	0.96	0.11	41
NF63	0.31	0.12	0.29	0.19	0.48	0.58	0.08	38
NF64	0.26	0.14	0.22	0.13	0.40	0.68	0.00	43
NF65	0.31	0.15	0.28	0.13	0.49	0.73	0.06	47
NF67	0.28	0.14	0.26	0.12	0.48	0.64	0.02	39
NF87	0.24	0.14	0.20	0.10	0.42	0.70	0.07	35
NF88	0.41	0.17	0.36	0.26	0.64	0.85	0.03	39
NF89	0.44	0.14	0.44	0.24	0.62	0.63	0.24	6
NF95	0.30	0.10	0.29	0.18	0.45	0.49	0.11	33
NF98	0.31	0.10	0.31	0.20	0.46	0.53	0.11	36
NF99	0.21	0.10	0.19	0.10	0.36	0.44	0.02	31

NOTE: Measurements were taken using passive electret ion chambers placed 1 m above ground level.



Note: Measurements made using EICs 1 m above ground level.

Figure 3-3. Monthly average radon concentrations at the YMP site from 1991 to 1995.

Location	Median (pCi L^{-1})	Maximum (pCi L^{-1})	Minimum (pCi L^{-1})	Source
Yucca Mountain	0.30	0.96	MDC[1]	YMP Data
UNLV Campus	0.34	0.60	0.11	YMP Data
Nevada	0.4	1.4	0.07	Price et al. (1994)
USA	0.39	1.11	0.06	Hopper et al. (1991)

1. Minimum detectable concentration

A preliminary dose assessment was made based on the average YMP radon concentration of 0.32 pCi L^{-1} as measured using EICs. To calculate the dose, radon concentration was converted to working level (WL). Working level is defined as any combination of short-lived radon ^{222}Rn progeny in one liter of air that will result in the emission of 1.3×10^5 MeV of potential alpha

$$WL = \frac{Rn * EF}{100} \qquad (1)$$

energy (NCRP 1988). Radon concentration is related to WL by the following:

Where: Rn = Radon concentration in pCi L^{-1}

EF = Equilibrium factor

The equilibrium factor is a measure that describes the degree of radioactive equilibrium between radon and its short-lived progeny, or in other words, the ratio of potential alpha energy concentration in air to that which would exist if all short-lived radon progeny were in equilibrium with the radon. The equilibrium factor was not measured for ambient air at Yucca Mountain, but was assumed to be 0.8 for outdoor air based on data presented in NCRP (1988). For the average YMP radon concentration the WL was calculated to be 0.0026 WL.

The exposure rate to workers is commonly expressed in the unit working level month (WLM), defined as the exposure rate of 1WL for a working month or 170 hours (NCRP 1988).

$$WLM = WL * \frac{Exposure\ Time\ (hours)}{170} \qquad (2)$$

The WLM can be calculated by:
Assuming an exposure of 0.0026 WL for one continuous year (8760 hours), the exposure rate was calculated to be 0.134 WLM. The WLM can be converted to effective dose equivalent (see glossary) using a dose conversion factor of one rem effective dose equivalent per WLM (NCRP 1993). A WLM of 0.134 yields an annual effective dose equivalent of 0.134 rem (134 mrem). In comparison, the NCRP (NCRP 1987) estimated that on average, a person in the U.S. receives 200 mrem effective dose equivalent annually from radon exposure. When considering a dose to a worker, the effective dose equivalent drops to 31 mrem based a 2040 hour working year (assuming a 170 hour working month).

3.2 CONTINUOUS RADON MONITORING

Continuous radon monitors were established at NF87 and NF06 primarily to study time-dependent radon fluctuations. Log-normal distribution of CRM data has been observed in other studies (Liu et al. 1996, EPA 1992). However, this is not the case for the CRM data from NF06 and NF87.

From 1993 to 1995, CRMs measured radon concentrations that ranged from below the system's minimum detectable concentration (nominally 0.05 pCi L^{-1}) to 0.89 and 1.32 pCi L^{-1} at NF87 and NF06, respectively (Table 3-5). The annual geometric mean concentrations were all within 1 geometric standard deviation of each other. Concentrations measured in 1993 using CRMs appeared to be significantly higher than concentrations in 1994 or 1995.

	NF87			NF06		
	1993	1994	1995	1993	1994	1995
GM[1]	0.17	0.07	0.08	0.11	0.08	0.06
GStd[2]	1.67	2.86	1.89	1.61	1.80	3.17
Median	0.17	0.08	0.08	0.12	0.09	0.06
10%[3]	0.11	0.03	0.05	0.08	0.06	0.02
90%[4]	0.24	0.14	0.13	0.16	0.12	0.10
Max	0.82	0.89	0.51	0.42	0.31	1.32
Min	-0.02	-0.03	0.00	-0.02	0.00	-0.07
Count	4054	6587	3919	4058	4899	3673

1. Geometric mean
2. Geometric standard deviation
3. 10th Percentile
4. 90th Percentile

However, the counts contributed by detector background (electronic noise, etc.) were not clearly defined until December 1993.

A strong diurnal trend in radon concentration was apparent at both NF06 and NF87 (Figure 3-4). The same sinusoidal pattern was exhibited each year, with radon concentrations highest in the early morning hours and lowest in the mid-afternoon. The percent difference between the highest and lowest hourly average concentrations at the stations ranged from between 39% to 74%. Diurnal fluctuations may be primarily a function of daily cycles in atmospheric stability (NCRP 1988). The rapid cooling of the desert ground at night creates temperature inversions leading to very stable nighttime conditions in the near-surface layers of air (TRW 1995). During these hours, vertical mixing of the atmosphere is poor, and radon emanating from soil is trapped

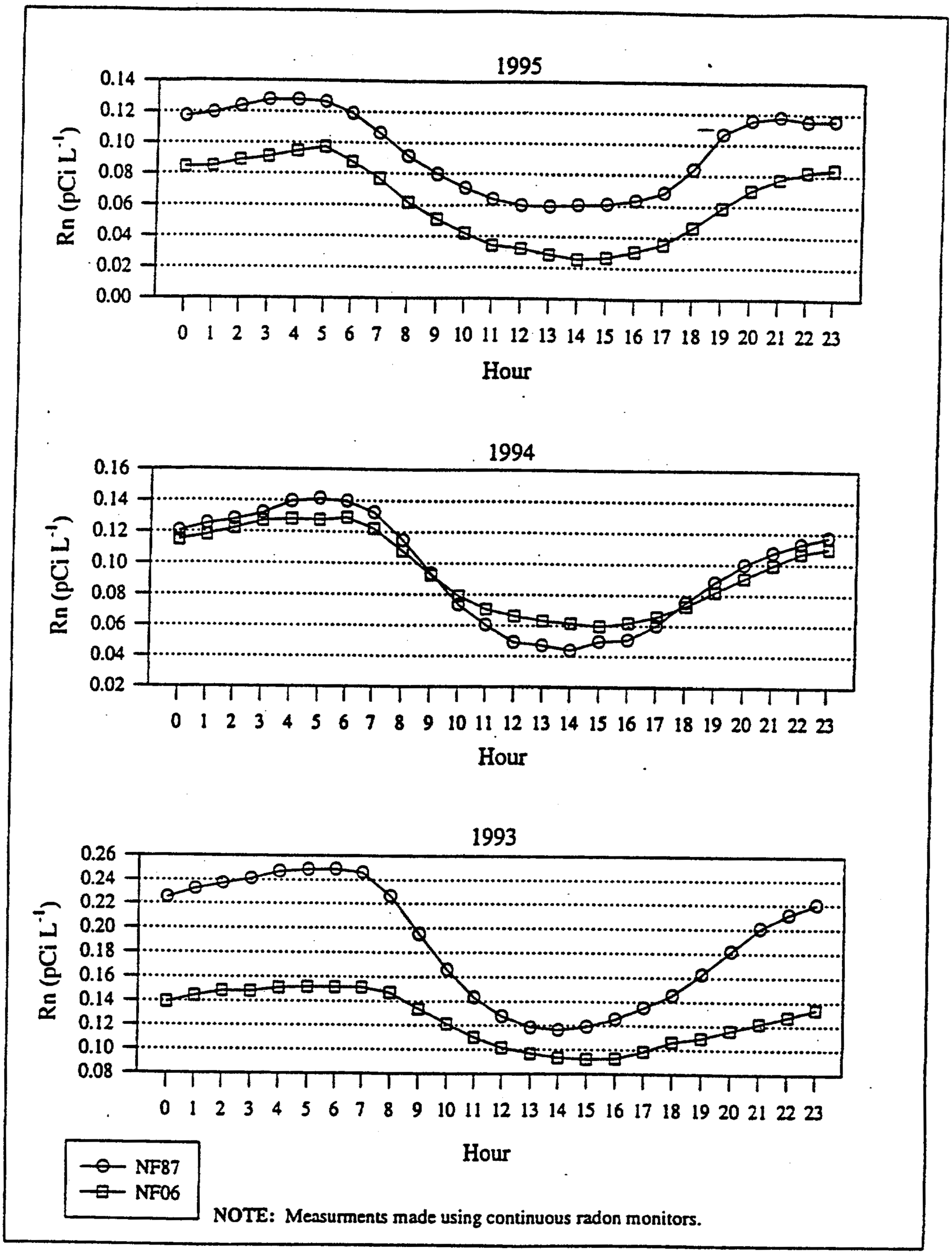
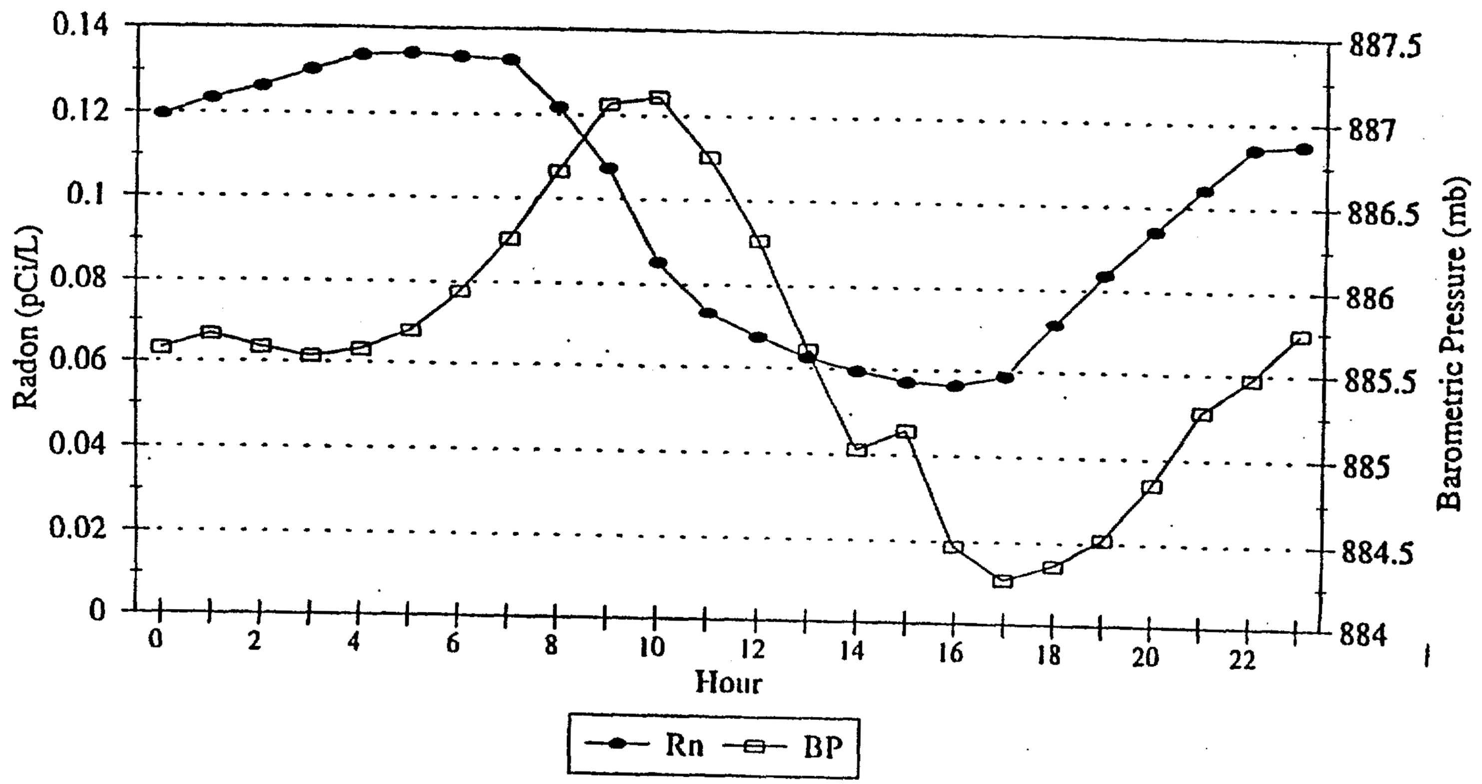


Figure 3-4. Diurnal fluctuation of radon concentrations at the YMP site.

near the ground, increasing near-surface radon concentrations. In the daytime, atmospheric vertical mixing increases. Convection currents and winds, created by solar heating of the ground surface, disperse radon into a larger volume of the atmosphere, effectively diluting the air concentration near the ground.

Average hourly radon concentrations were not significantly correlated to hourly barometric pressure (Figure 3-5). However, barometric pressure did show a similar diurnal fluctuation pattern. Barometric pressure appeared to peak in mid-morning, and was lowest late in the afternoon. Though not clearly shown in this graph, pressure gradients between soil and the atmosphere have been shown to affect radon emanation from soil. Short-term changes in radon flux across the air/soil surface interface have been shown to substantially increase in response to sudden drops in barometric pressure, as soil gas is drawn from the upper soil layers (Kraner 1964, Schery et al. 1984, Schuman et al. 1990). However, this effect is temporary, slowing as the pressure between soil and air equilibrate and as the upper layers of soil are depleted of radon. High pressure, on the other hand, tends to decrease radon emanation from soil.

Seasonal trends of the CRM data were similar to the trend observed in the EIC radon data (Figure 3-6). Concentrations appeared to peak in the late fall - early winter months, and were generally lowest in summer.



NOTE: Data was collected between August and October 1994.

Figure 3-5. Average hourly radon concentration and barometric pressure at station NF06.

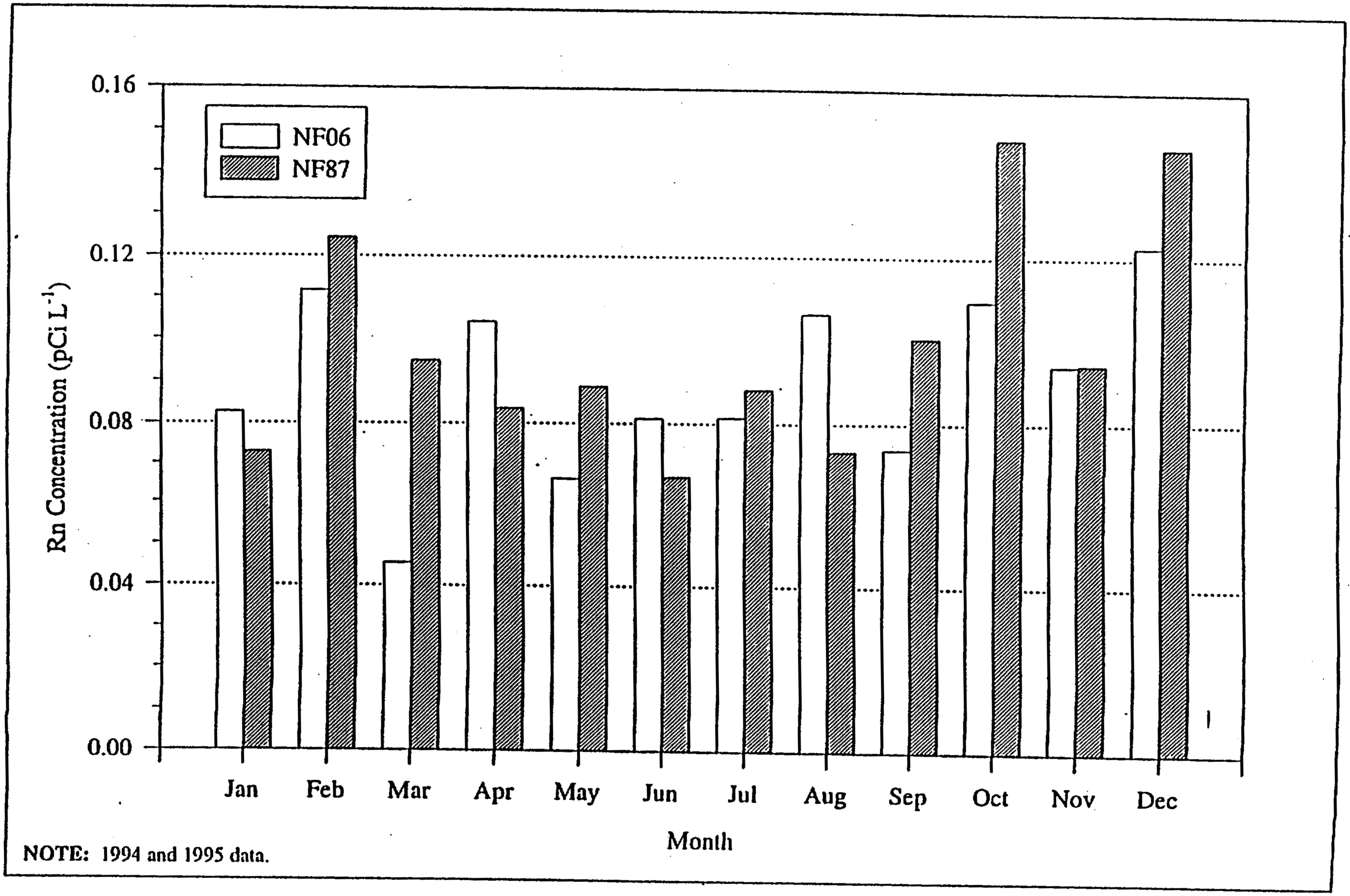
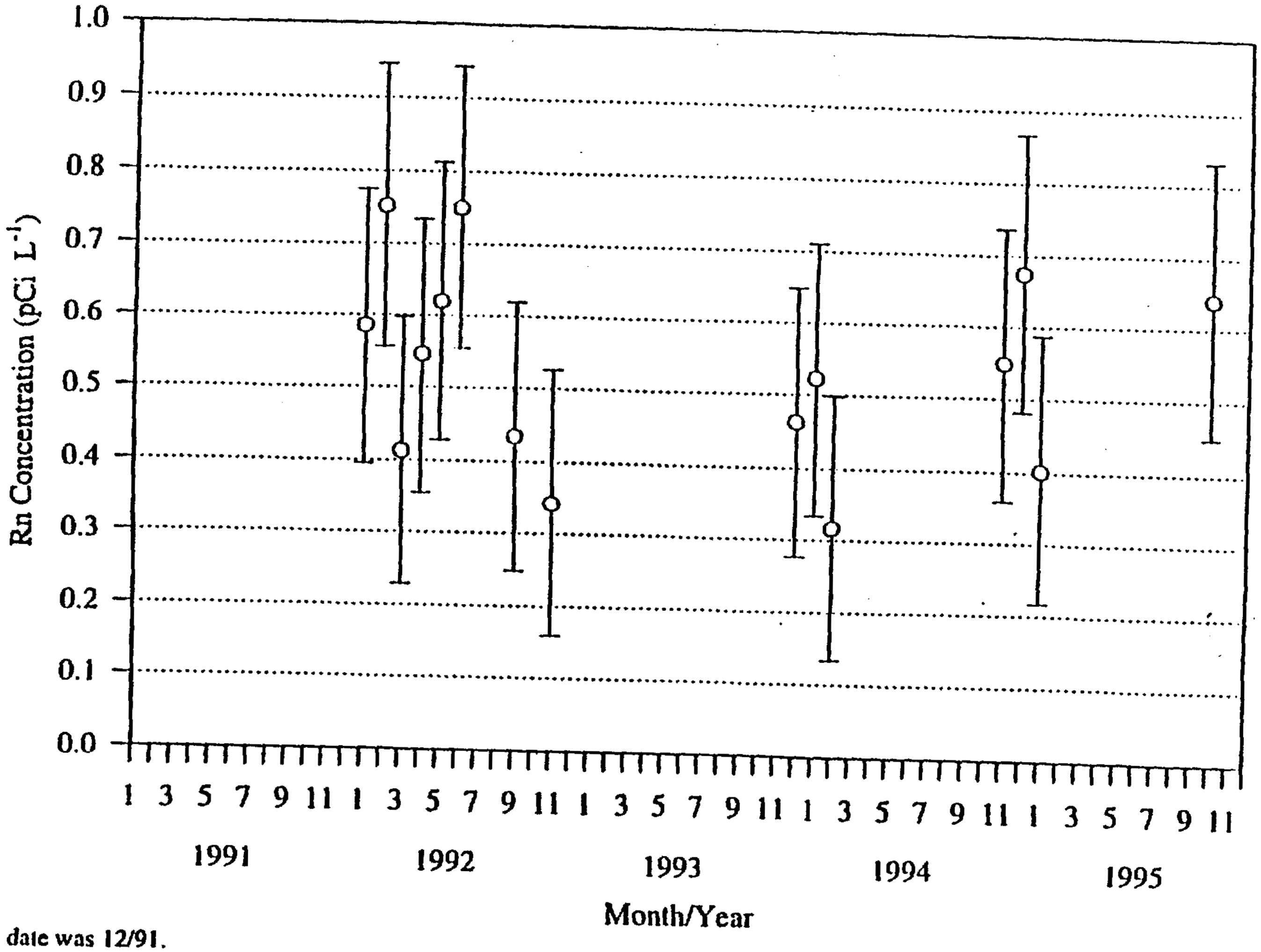
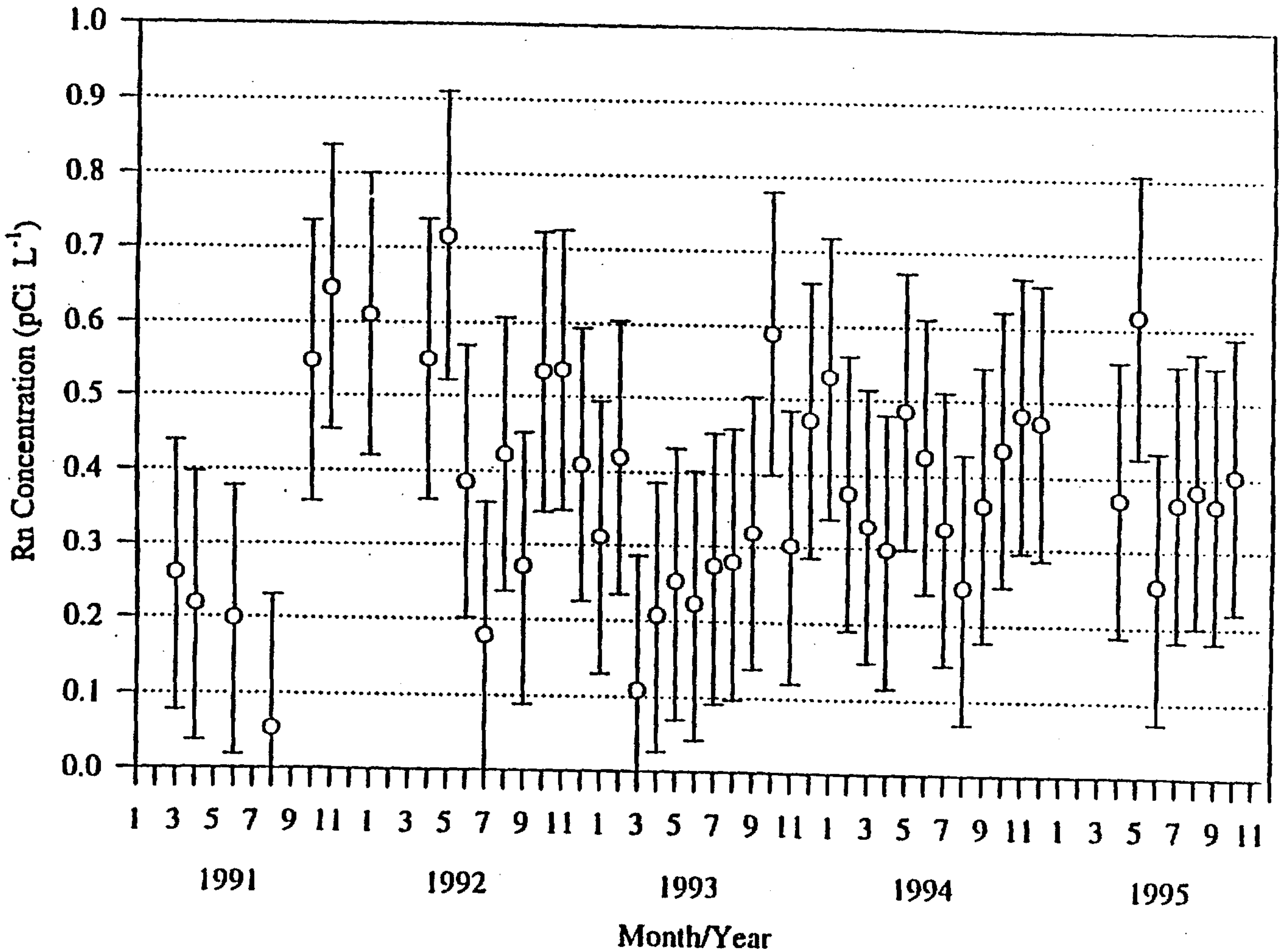


Figure 3-6. Monthly average radon concentrations at stations NF06 and NF87.



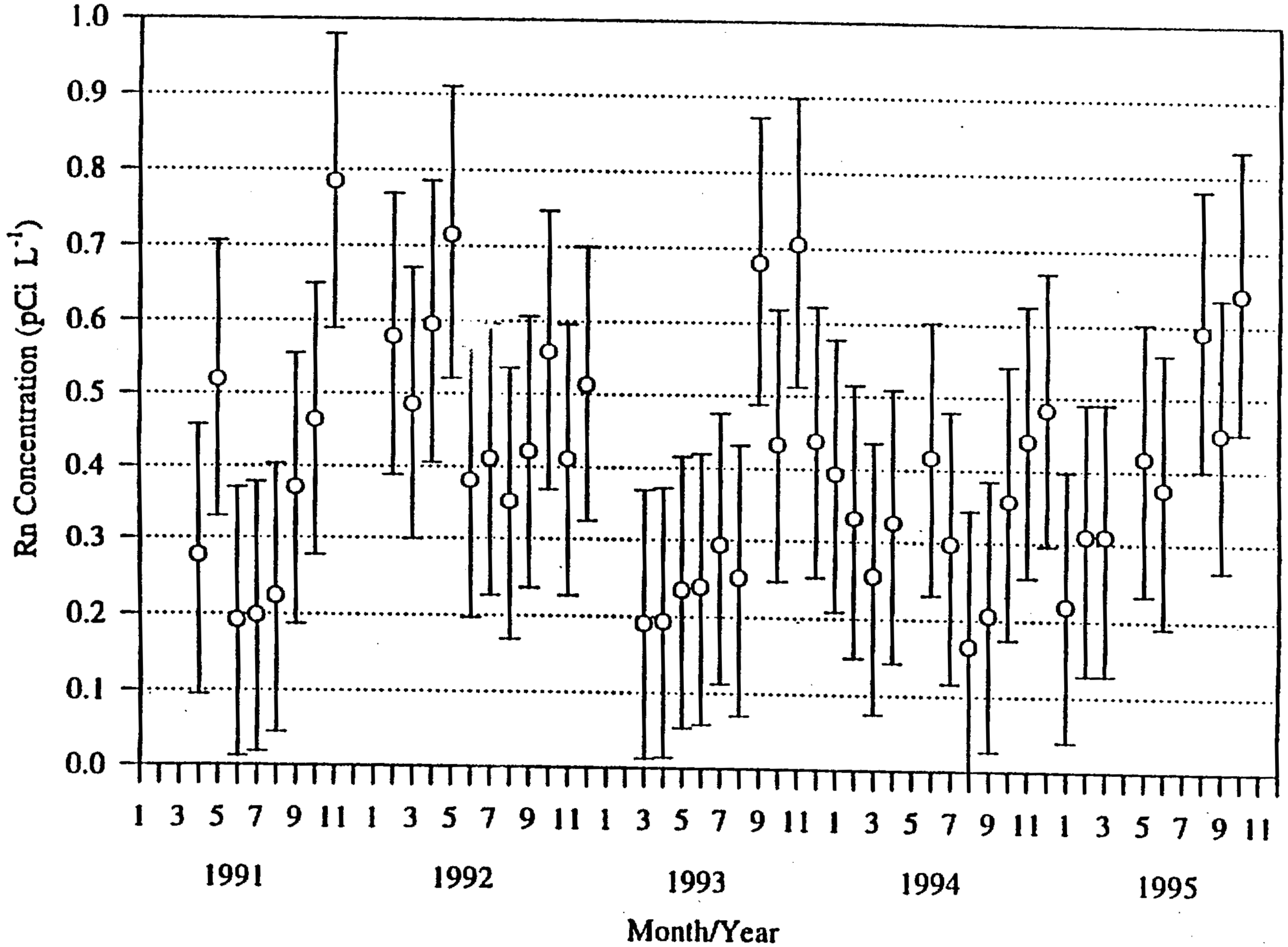
NOTE: Start date was 12/91.
Error Bars represent total measurement error.

Figure B-4. Monthly EIC radon concentrations at station NF38.



NOTE: Start date was 3/91.
Error Bars represent total measurement error.

Figure B-5. Monthly EIC radon concentrations at station NF60.



NOTE: Start date was 3/91.
Error Bars represent total measurement error.

Figure B-6. Monthly EIC radon concentrations at station NF61.

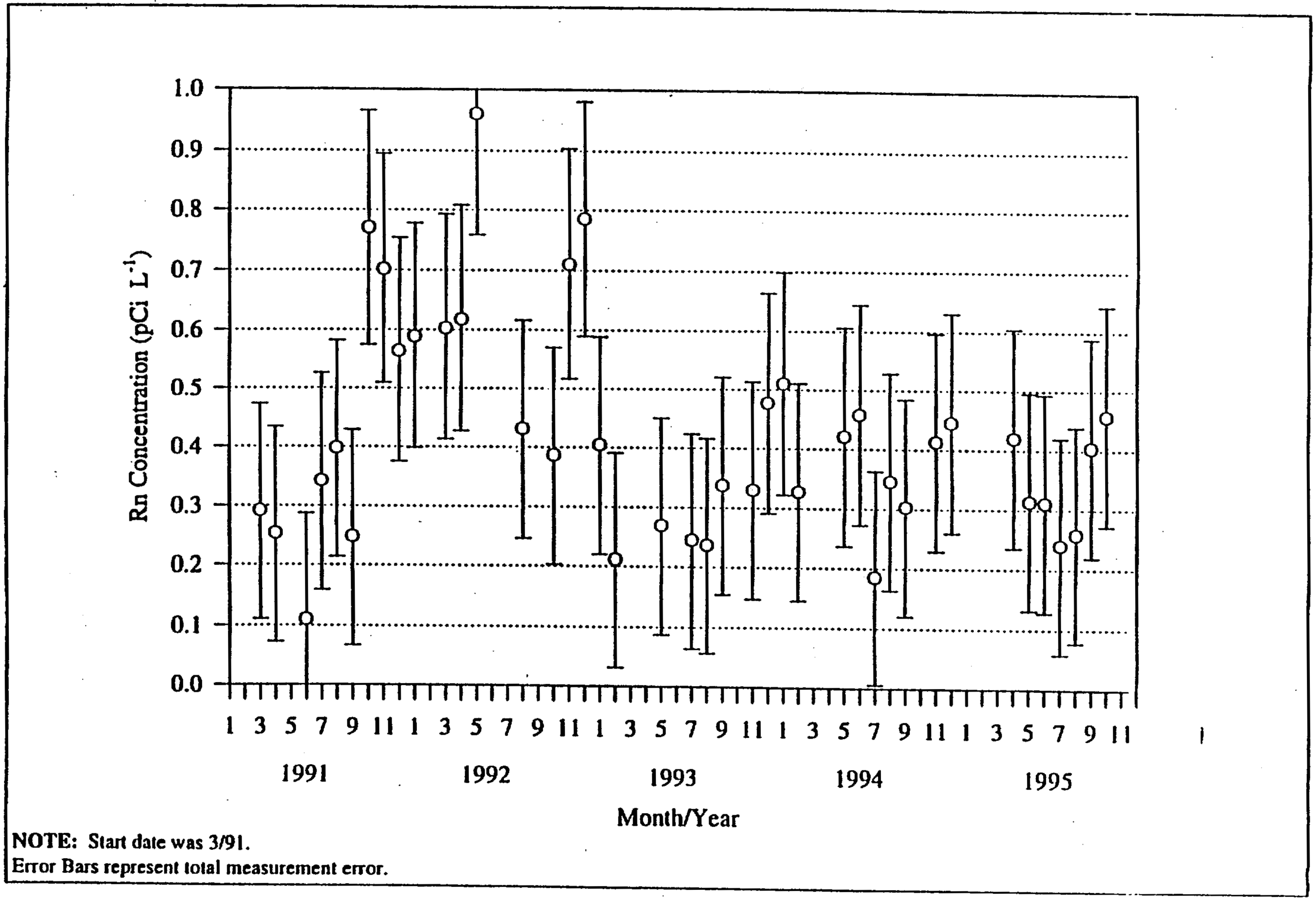


Figure B-7. Monthly EIC radon concentrations at station NF62.

4.0 CONCLUSIONS AND RECOMMENDATIONS

Overall, radon concentrations at the Yucca Mountain site fall well within the range for regional and national concentration averages. While not conclusive, regional atmospheric radon concentrations to date, do not appear to have changed significantly since the inception of site characterization activities. Additional investigation is needed to determine the reason behind trends observed at some of the monitoring stations.

Further analysis is also needed to clarify the effects of site-specific meteorological factors on radon levels, cycles and transport at the Yucca Mountain site. A preliminary analysis of one factor, barometric pressure, is presented in this report. Discussions with the meteorological group indicated that additional data may be available to do further detailed analyses. Knowledge of the factors affecting radon emanation rates, trends and cycles in the environment will make the identification and assessment of changes in ambient radon levels easier and more reliable.

The majority of the sampling locations were established in 1991 and 1992, before many of the current site activities were started. General radon levels in the area have been established under the current sampling design. However, given the current availability of information on factors such as site meteorological conditions, area use and occupancy, and other pertinent data, future work should be focused on those areas that have the greatest potential for influencing ambient radon conditions. Specific sampling objectives for an area should be well defined and a sampling program developed to meet those objectives.

It is recommended that monitoring in the area around the north portal of the ESF be reviewed. The ESF is likely the primary site characterization activity that could potentially influence radon inventories in the area. Currently, radon produced underground is vented to the atmosphere through the ESF ventilation stack located at the north portal. Sampling in this area should be designed to track radon levels, trends and distribution patterns in the immediate vicinity of the ventilation stack as this is the area that has the highest potential to be impacted by ESF radon emissions. To date, the majority of the sampling has focused on the area south of the portal. A review of existing monitoring station locations, and the activities occurring near the stations, may identify stations that could be relocated to meet current sampling goals.

It is also recommended that a sampling program be designed to establish, quantitatively, atmospheric radon concentration levels in the immediate vicinity of the proposed south portal of the ESF. Like the north portal, the south portal is a potential point source of radon emissions to the atmosphere. In order to assess possible changes in radon conditions, a statistically valid sampling regime designed specifically to estimate levels, trends, and patterns of radon in the area prior to construction should initiated. Several monitoring stations are located north of the area, however, currently there is only one station in the immediate area.

APPENDIX A

PASSIVE ELECTRET ION CHAMBER (EIC) CALCULATIONS

For the this report all EIC radon concentrations and measurement errors were calculated based on the equations and constants given below. All the equations and conversion factors come the from E-PERM® System Manual (Rad Elec 1991, 1994).

Radon Concentration Calculation

Converting the change in electret voltage to a radon concentration is a two step process. First a calibration factor (CF) is determined by:

$$CF = A + B * \frac{(I+F)}{2} \qquad (3)$$

Where:

CF = Calibration factor (change in electret voltage per pCi L^{-1} in 1 day)
A = Manufacturer provided calibration constant for a particular EIC configuration (A = 1.6978 for YMP configuration).
B = Manufacturer provided calibration constant for a particular EIC configuration (B = 0.0005742 for YMP configuration).
I = Initial electret voltage
F = Final electret voltage

The radon concentration is then calculated by:

$$Rn = \frac{(I - F)}{CF * D} - (C * G) \qquad (4)$$

Where:

Rn = Radon concentration in pCi L^{-1}
I = Initial electret voltage
F = Final electret voltage
CF = Calibration factor (as calculated in equation 1 above)
D = Exposure period in days
C = Manufacturer provided gamma conversion factor to convert μR/h to pCi L^{-1}
(C = 0.087 for YMP configuration)
G = Ambient gamma radiation exposure rate (μR h^{-1}).

The ambient gamma radiation exposure rates used for the radon concentration calculations were based on mean gamma exposure rates measured using high pressure ion chambers (HPIC). Gamma exposure data were collected from 1991-1995 at stations NF87, NF06, FF12 and FF83 and reported in the report Ambient Gamma Exposures At The Yucca Mountain Site

(TRW 1996a). Exposures rates at a given site appeared to be relatively stable over time with coefficients of variation of less than 10% for all the sites. For stations other than those listed above, the gamma exposure rate was estimated as the midpoint of the mean exposure rates observed at NF06 and NF87.

Measurement Error Calculation

The total measurement error associated with any one radon concentration is estimated as follows:

$$EO = \sqrt{E1^2 + E2^2 + E3^2} \qquad (5)$$

Where:

E1 = Error in the radon concentration estimate due to system electret and ion chamber uncertainties
E2 = Error associated with the electret voltage reader
E3 = Error associated with background gamma exposure estimate

the components of the total measurement error are explained in more detail below.

Electret and Ion Chamber Error (E1)

The first component of the total error is error associated with the system electret and ion chamber. This includes error due to electret instability, variation in electret thickness, variation in ion chamber volume and error in the manufacturer supplied calibration factors. According to the manufacturer, the maximum error associated with EIC system itself is less than 5%. Therefore, the error in a concentration estimate due to the system (E1) is:

$$E1 = 0.05 * \frac{(I - F)}{(CF * D)} \qquad (6)$$

Where I, F, CF and D are the parameters defined in equations 1 and 2 above.

Electret Reader Error (E2)

The second component is error associated with the instrument used to measure the electret voltage. According to the manufacturer, the accuracy of the electret reader is ±1 volts over its entire range. Two electret voltage readings (initial and final) are needed to make a concentration calculation.

Therefore, the fractional error associated with making voltage two readings is:

$$\frac{\sqrt{1^2+1^2}}{I - F} = \frac{1.4}{I - F} \qquad (7)$$

and the error in a radon concentration due to the electret reader (E2) then is:

$$E2 = \frac{1.4}{I - F} * \frac{I - F}{CF * D} = \frac{1.4 * (I - F)^2}{CF * D} \qquad (8)$$

Gamma Exposure Error (E3)

The third component of the total measurement error is the error associated with the gamma background estimation. As stated above, data reported in TRW (1996a) were used for gamma background subtraction in EIC radon concentration calculations. The coefficient of variation (mean divided by the standard deviation) in the gamma radiation at any YMP HPIC site from 1991 to 1995 was reportedly less than 10%. Given that, the error due to gamma background (E3) in a radon concentration calculation is determined by:

$$E3 = CV * C * G \qquad (9)$$

Where:

CV = Coefficient of Variation in gamma background exposure rate at a site. For stations NF06, NF87, FF12 and FF83 the CV used was the same as that reported in TRW (1996a). The CV for these sites were all less than 0.10 (10%). For other stations, a CV of 0.10 was used in the error calculation. This is likely a conservative estimate of the error based on the empirical gamma exposure data collected at YMP sites from 1991 to 1995.

C = Manufacturer provided gamma conversion factor to convert μR/h to pCi L^{-1}
(C = 0.087 for the YMP configuration)

G = Ambient gamma radiation exposure rate (μR h^{-1}).

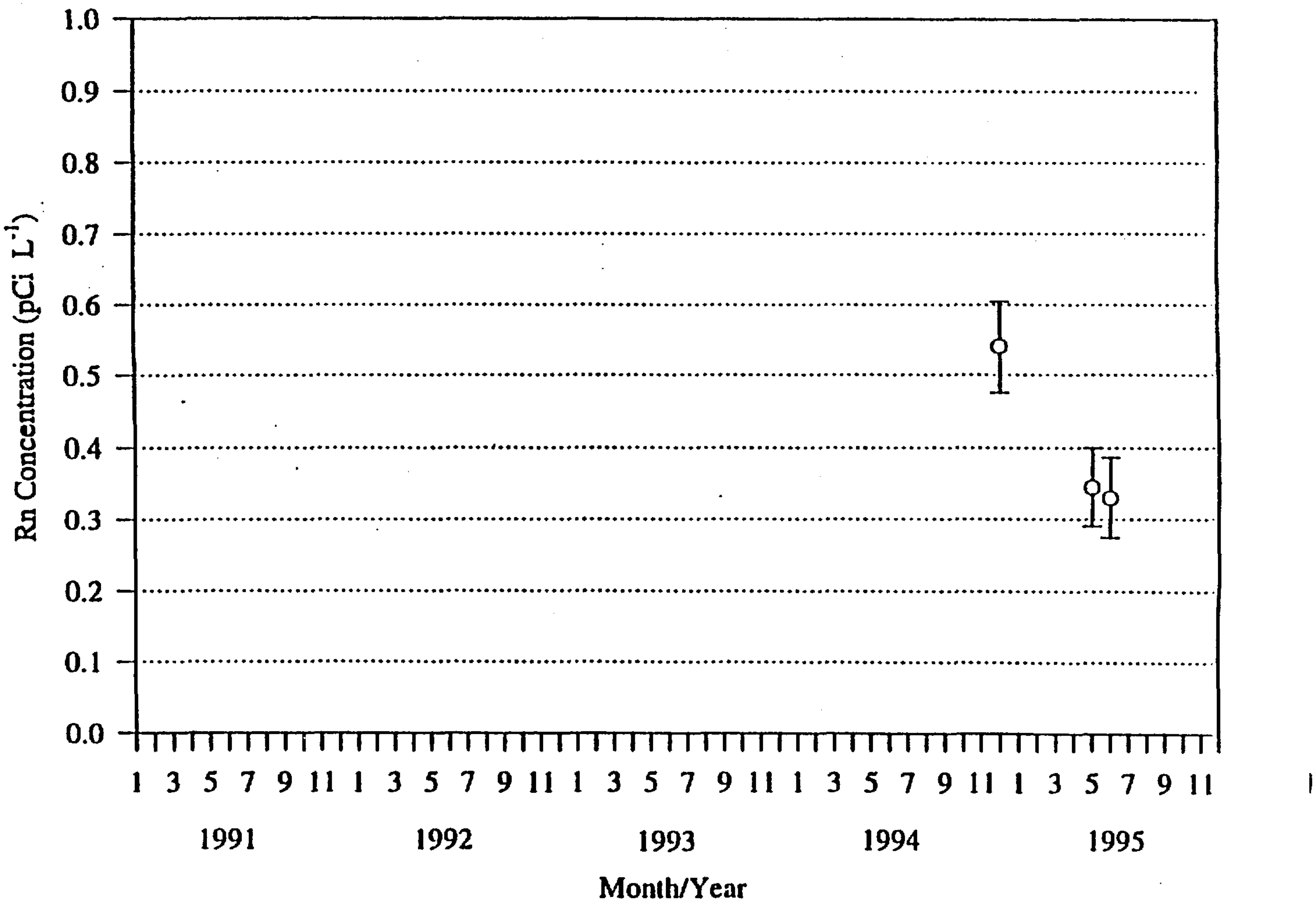
APPENDIX B

SUPPLEMENTARY TABLES AND FIGURES

Table B-1. Start dates for YMP radon monitoring stations.

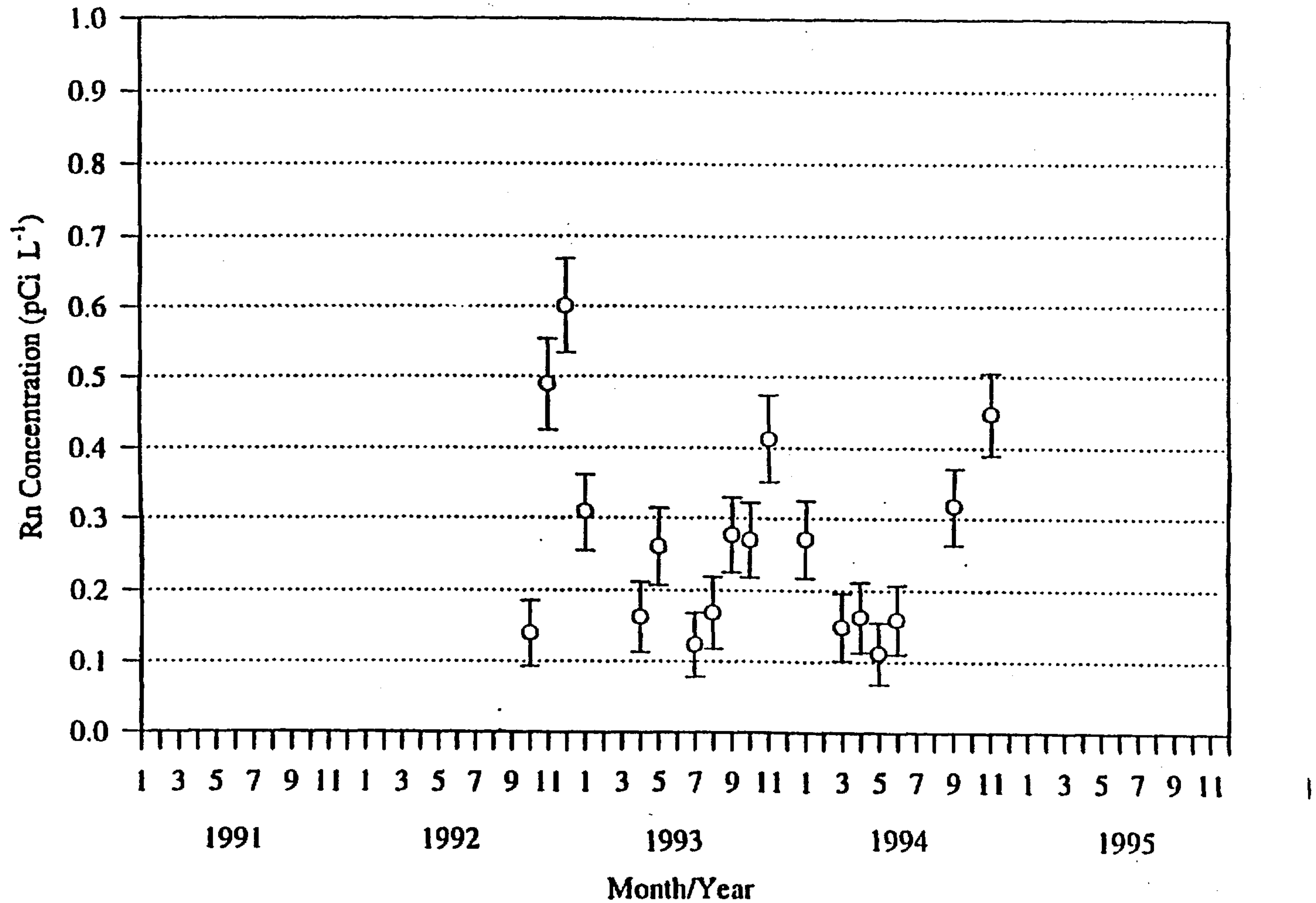
Site	Start Date	Site	Start Date
NF06	3/91	NF89	12/91[1]
NF38	12/91	NF95	6/92
NF60	3/91	NF98	6/92
NF61	3/91	NF99	6/92
NF62	3/91	NF100	6/92
NF63	3/91	NF101	6/92
NF64	3/91	NF102	6/92
NF65	3/91	NF108	4/93
NF67	3/91	FF12	12/94[2]
NF87	12/91	FF83	10/92[3]
NF88	12/91		

1. Last data collected 10/92
2. Last data collected on 6/95
3. Last data collected on 10/94



NOTE: Start date was 12/94.
Error Bars represent total measurement error.

Figure B-1. Monthly EIC radon concentrations at station FF12.



NOTE: Start date was 10/92.
Error Bars represent total measurement error.

Figure B-2. Monthly EIC radon concentrations at station FF83.

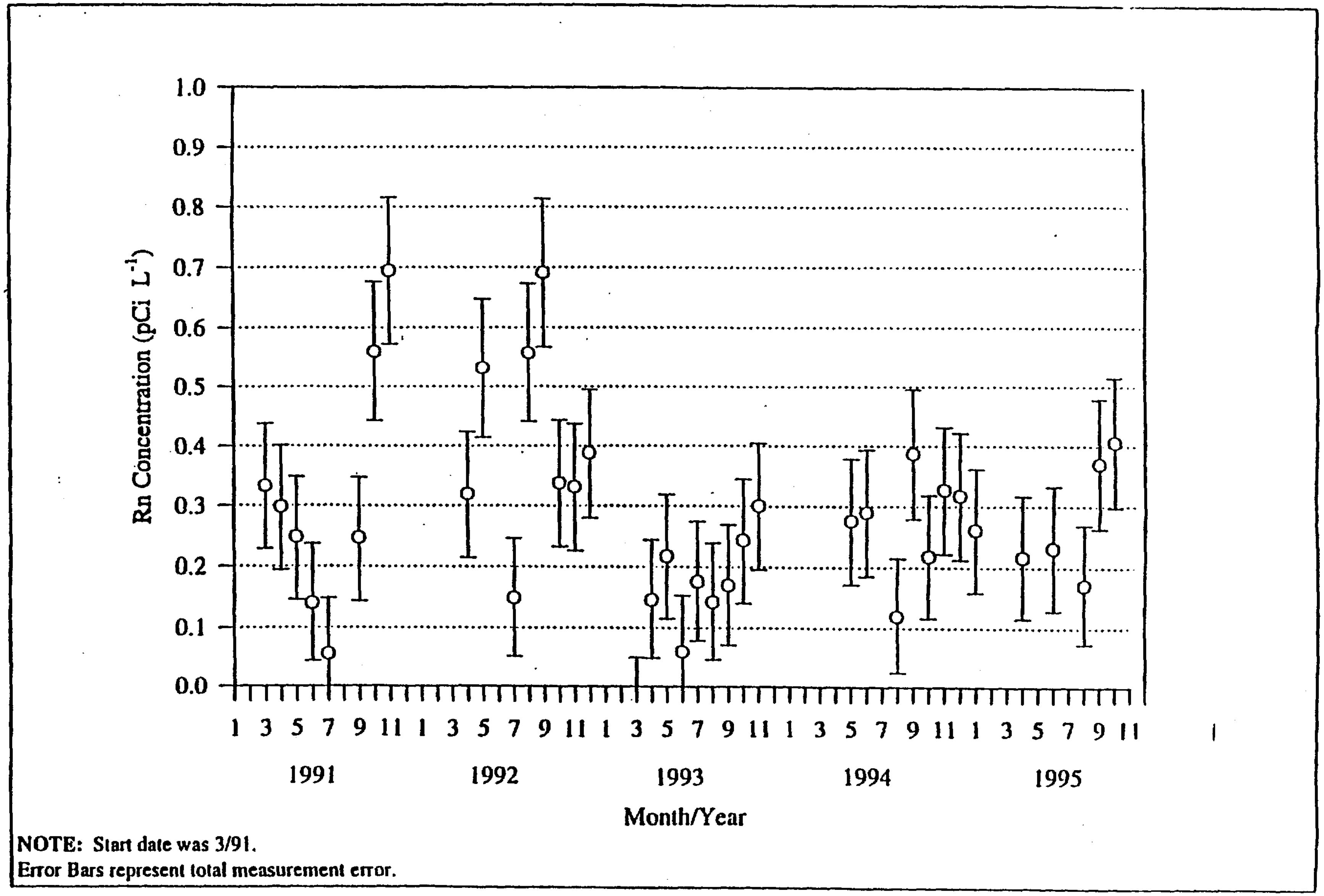
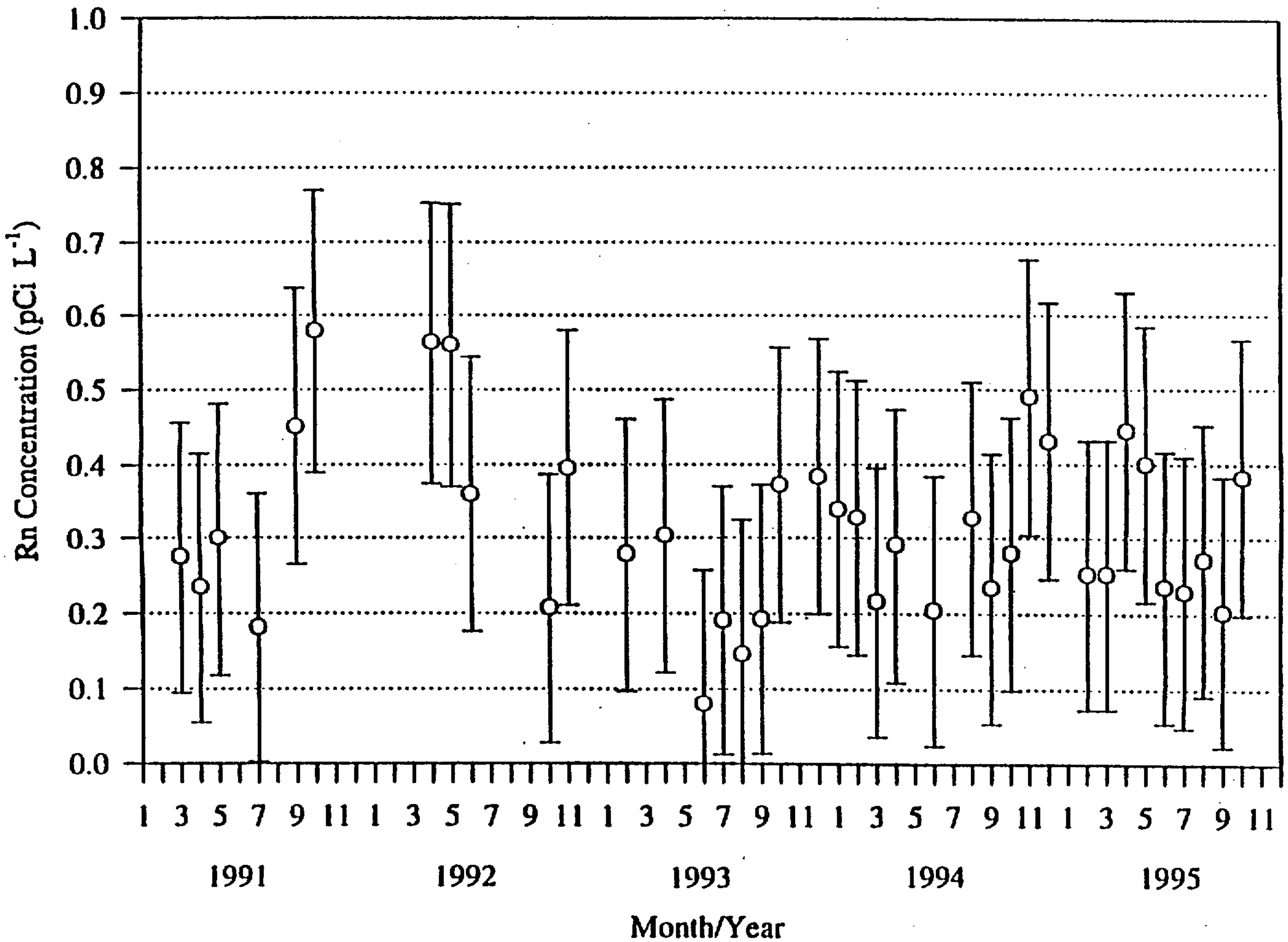


Figure B-3. Monthly EIC radon concentrations at station NF06.



NOTE: Start date was 3/91.
Error Bars represent total measurement error.

Figure B-8. Monthly EIC radon concentrations at station NF63.

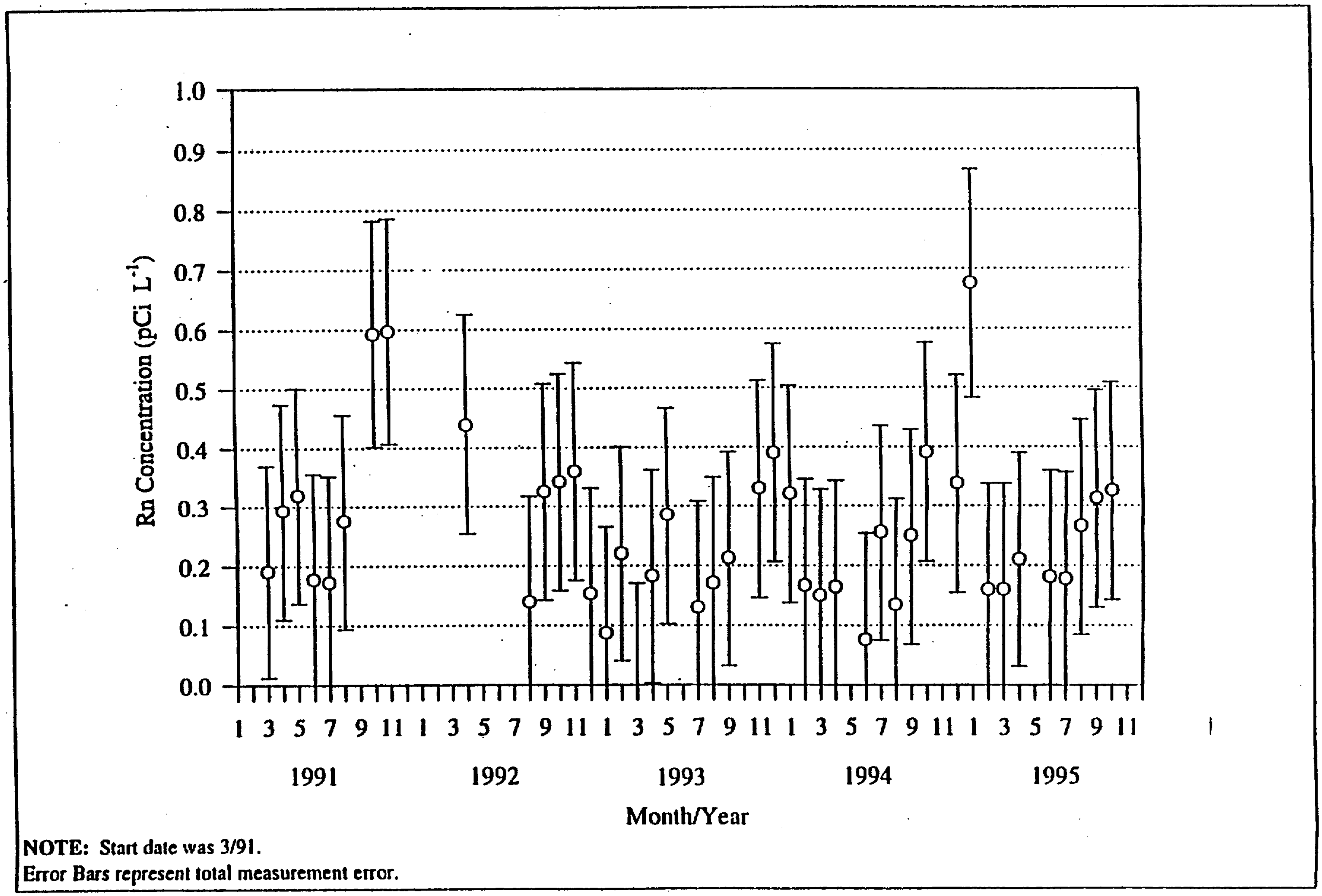


Figure B-9. Monthly EIC radon concentrations at station NF64.

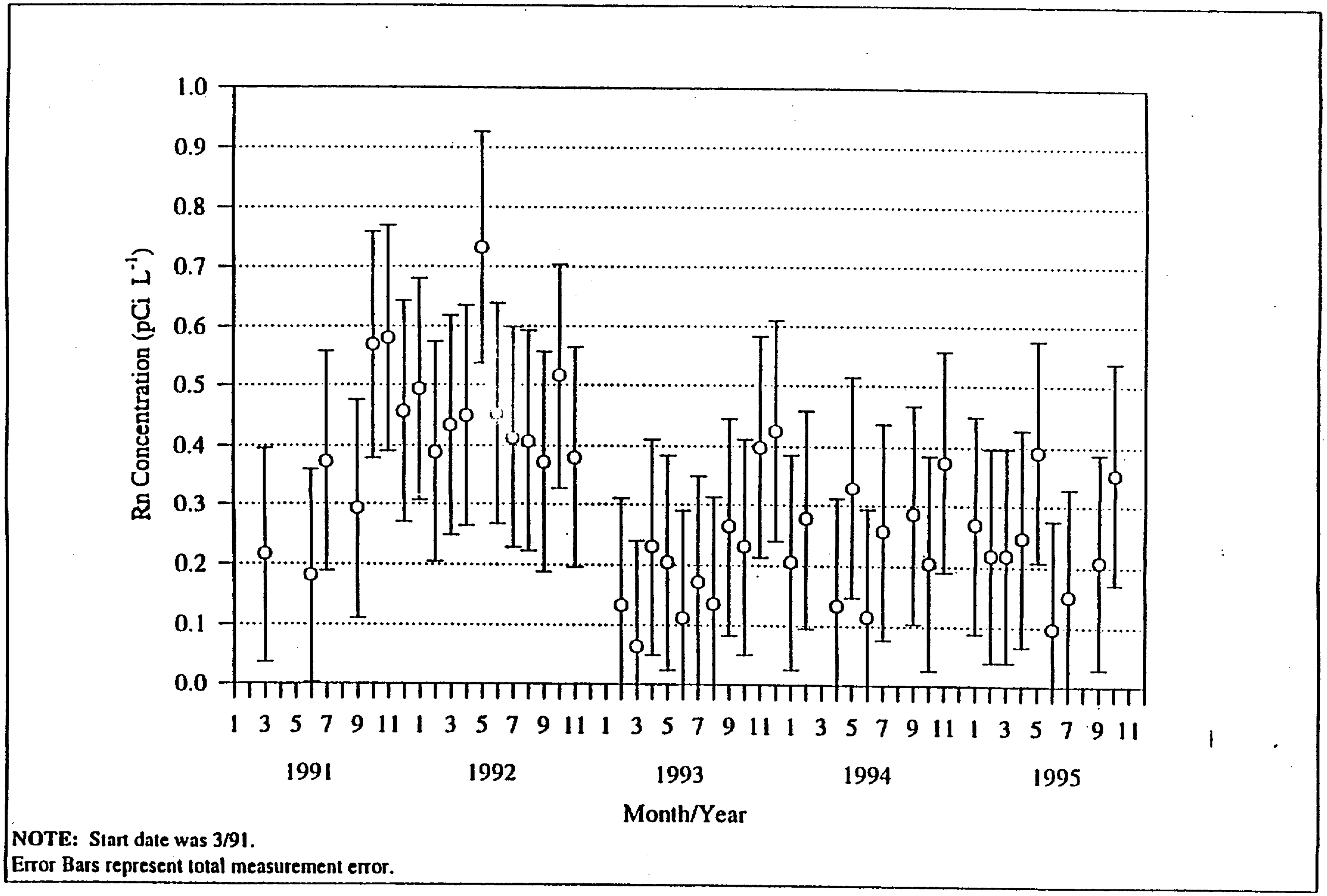
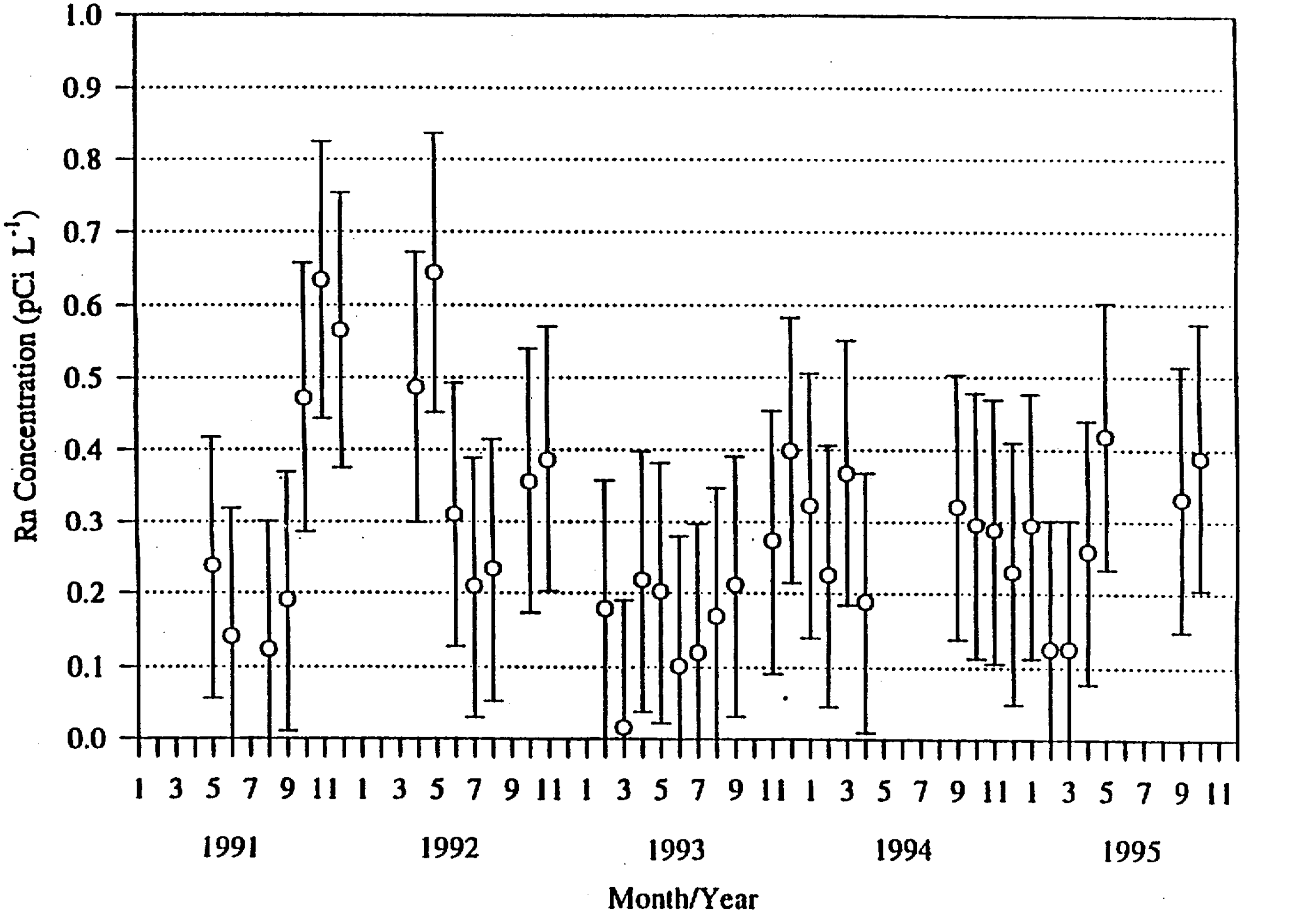
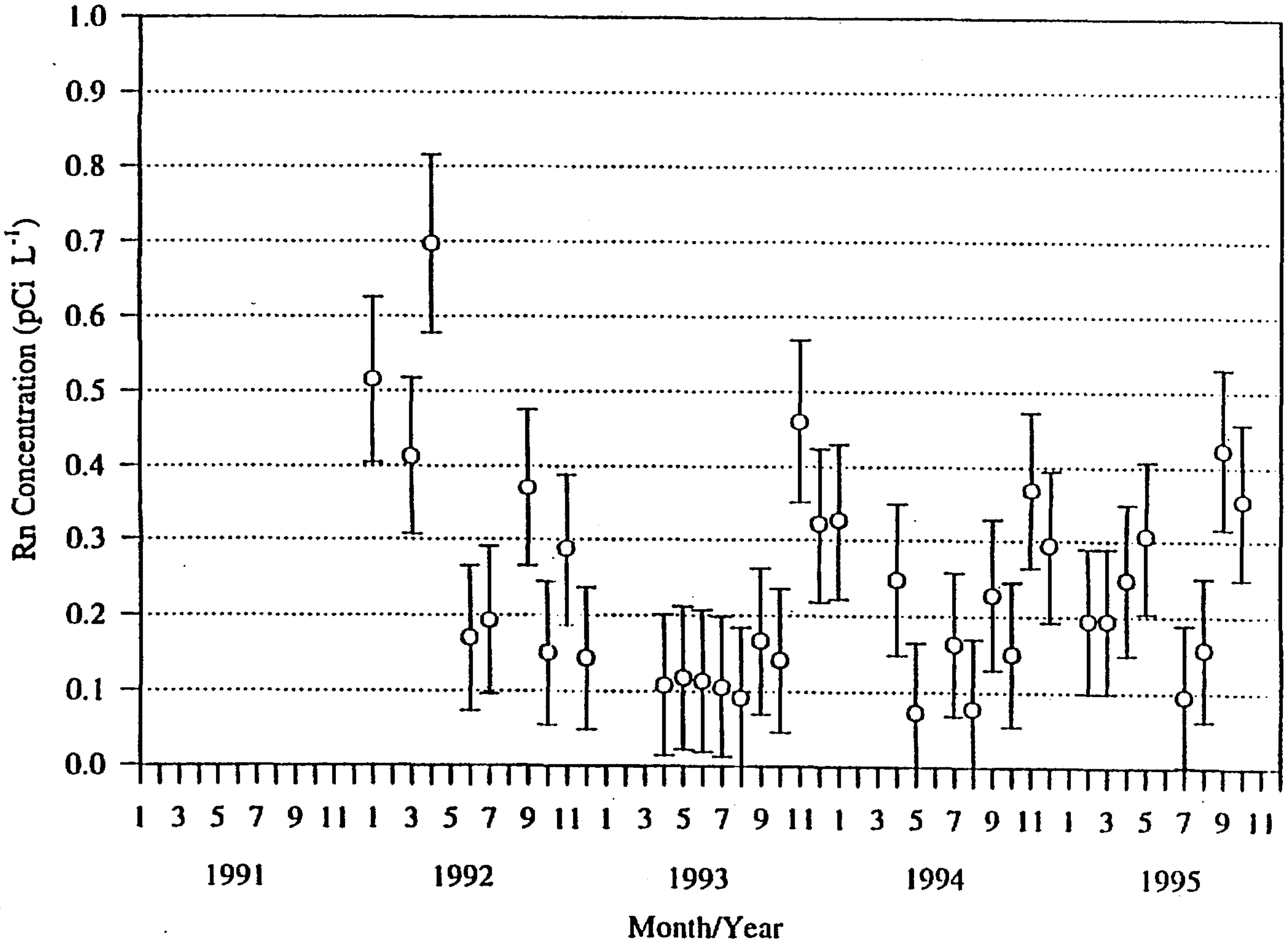


Figure B-10. Monthly EIC radon concentrations at station NF65.



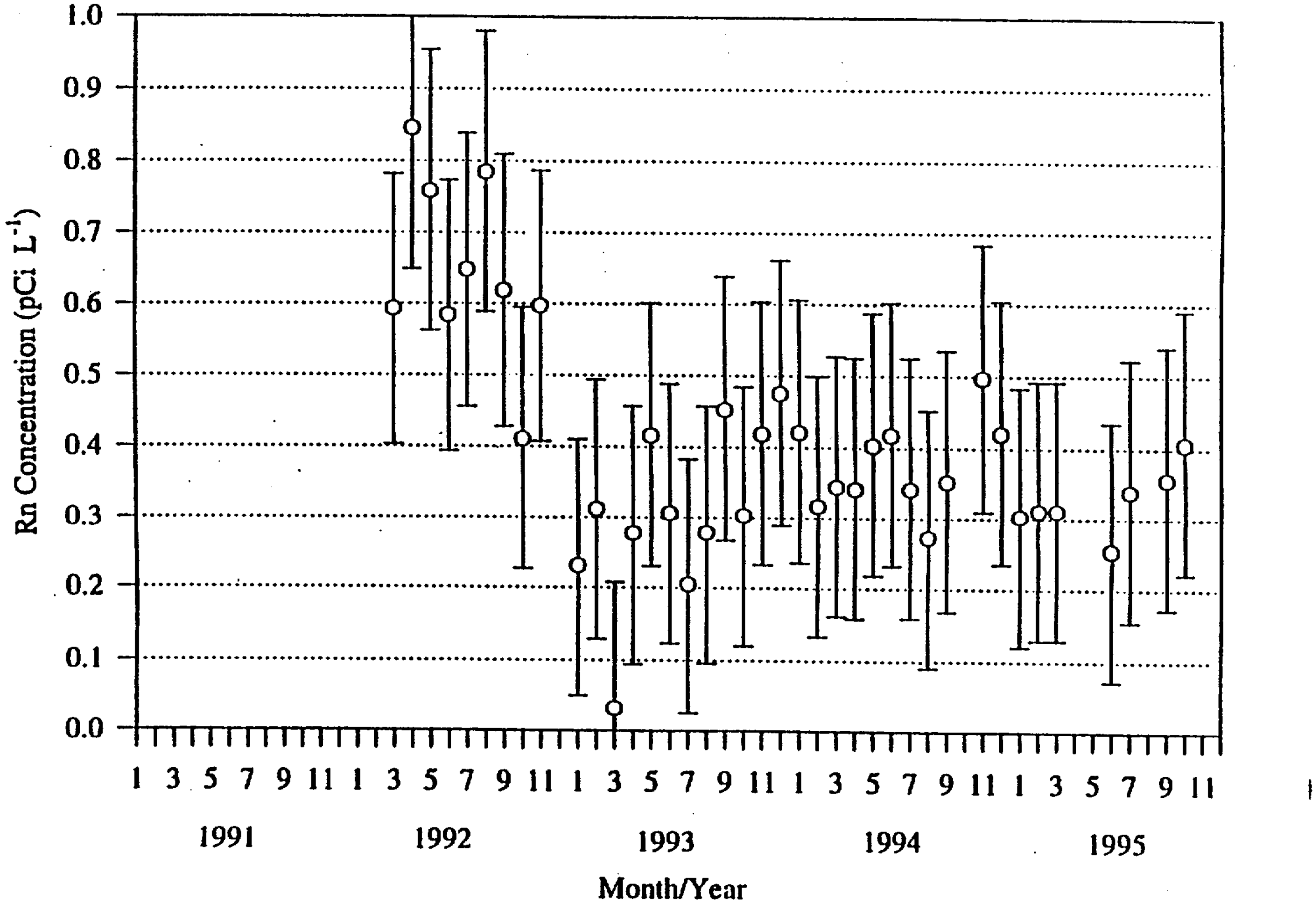
NOTE: Start date was 3/91.
Error Bars represent total measurement error.

Figure B-11. Monthly EIC radon concentrations at station NF67.



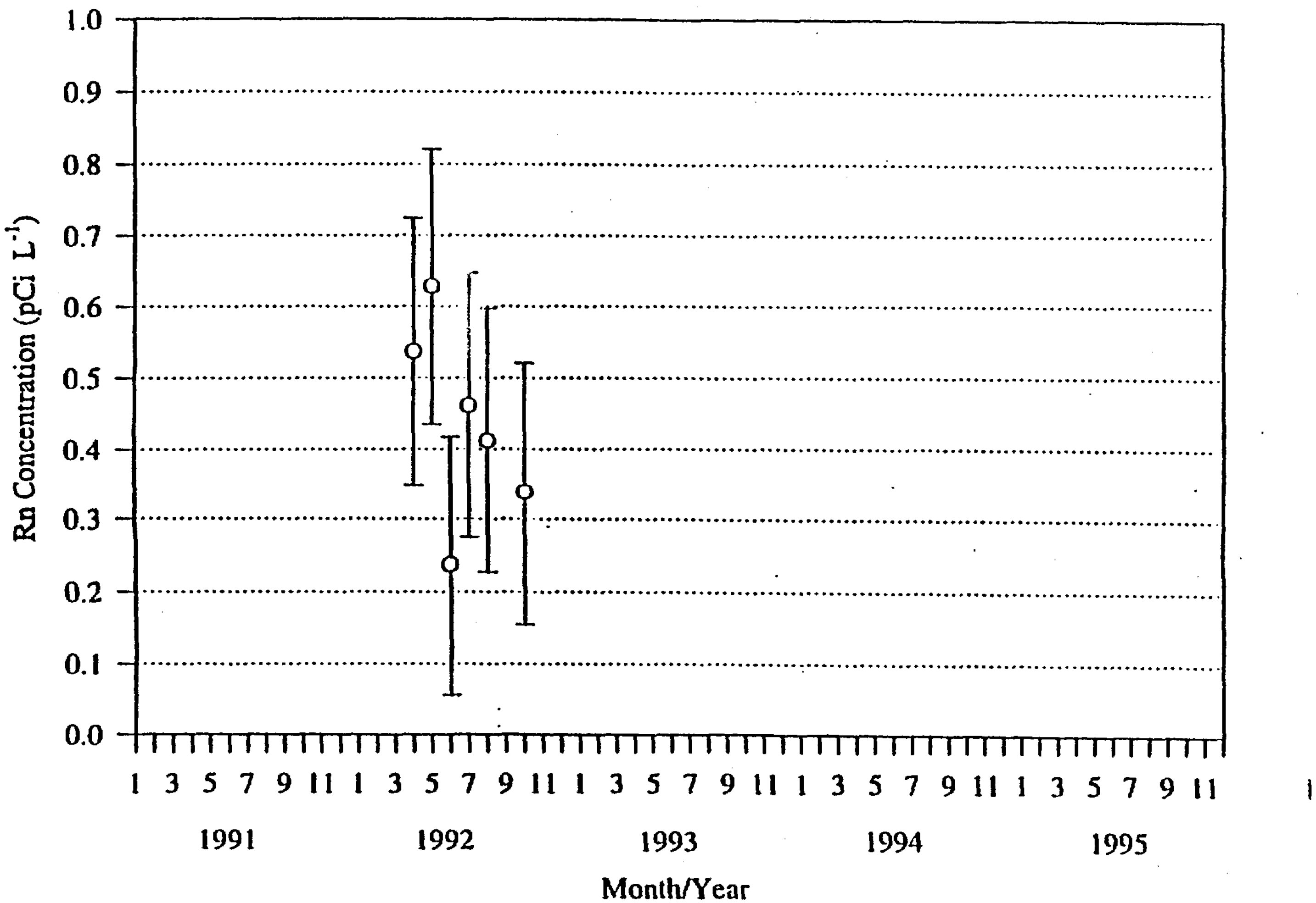
NOTE: Start date was 12/91.
Error Bars represent total measurement error.

Figure B-12. Monthly EIC radon concentrations at station NF87.



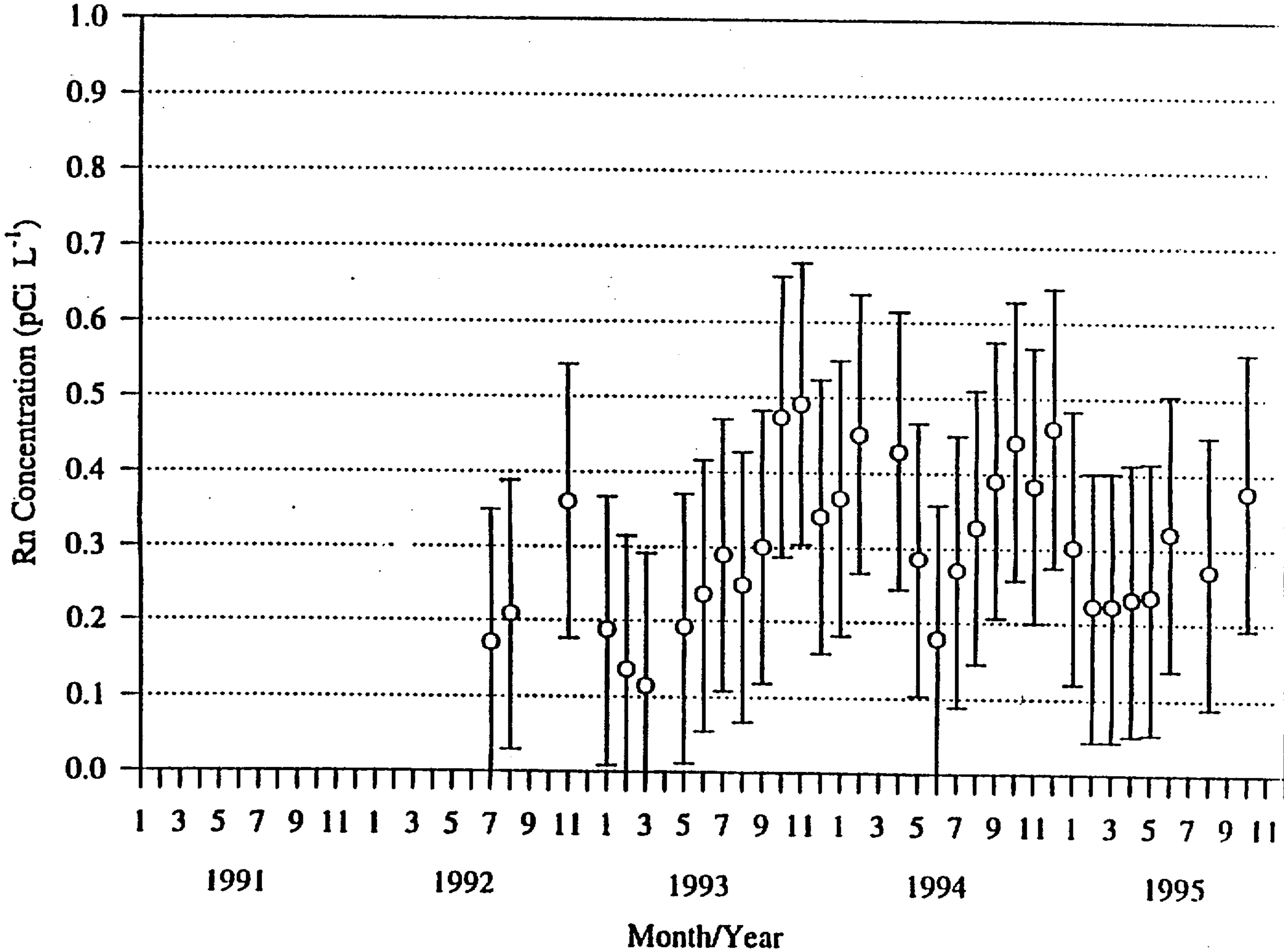
NOTE: Start date was 12/91.
Error Bars represent total measurement error.

Figure B-13. Monthly EIC radon concentrations at station NF88.



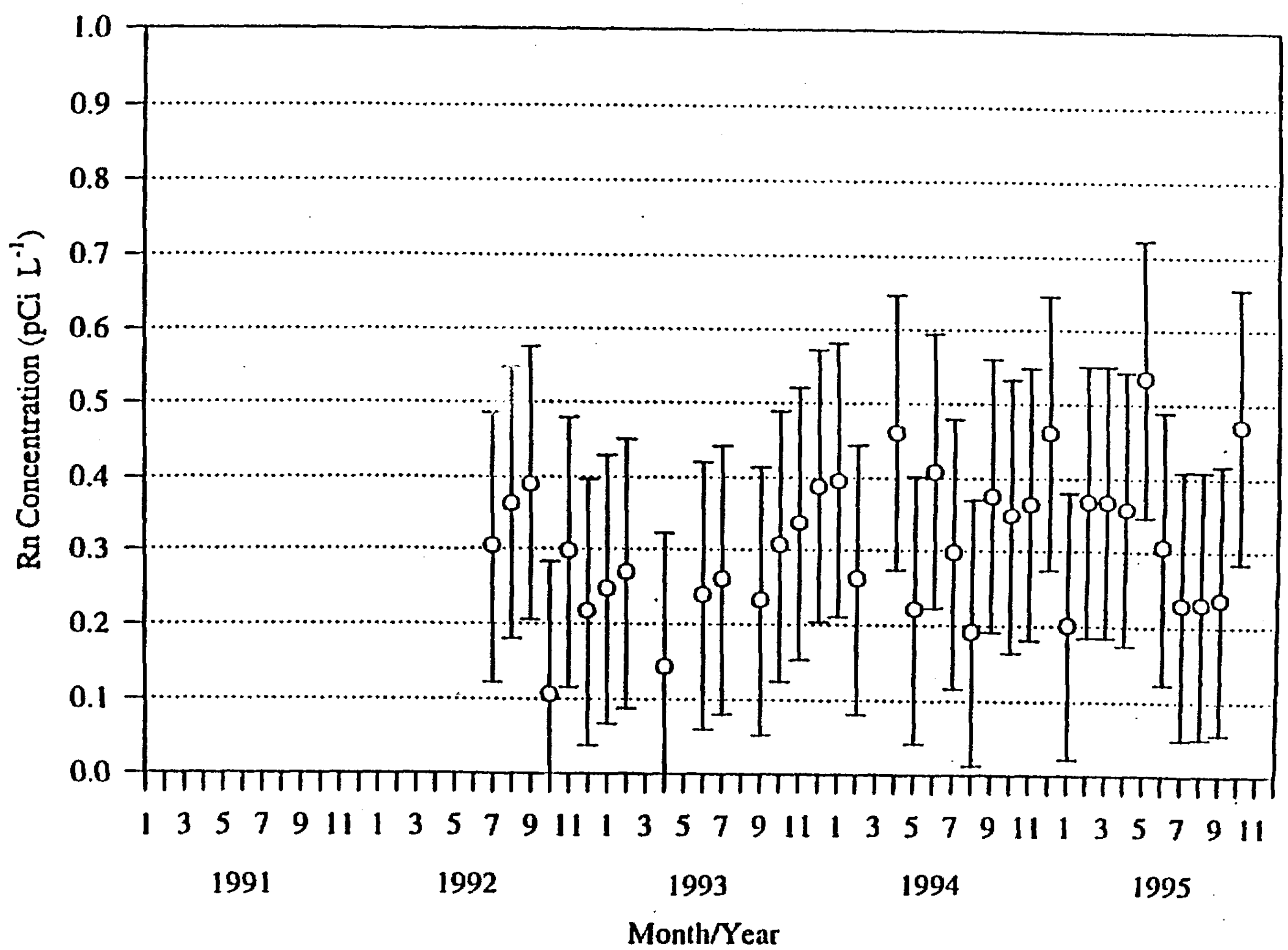
NOTE: Start date was 12/91.
Error Bars represent total measurement error.

Figure B-14. Monthly EIC radon concentrations at station NF89.



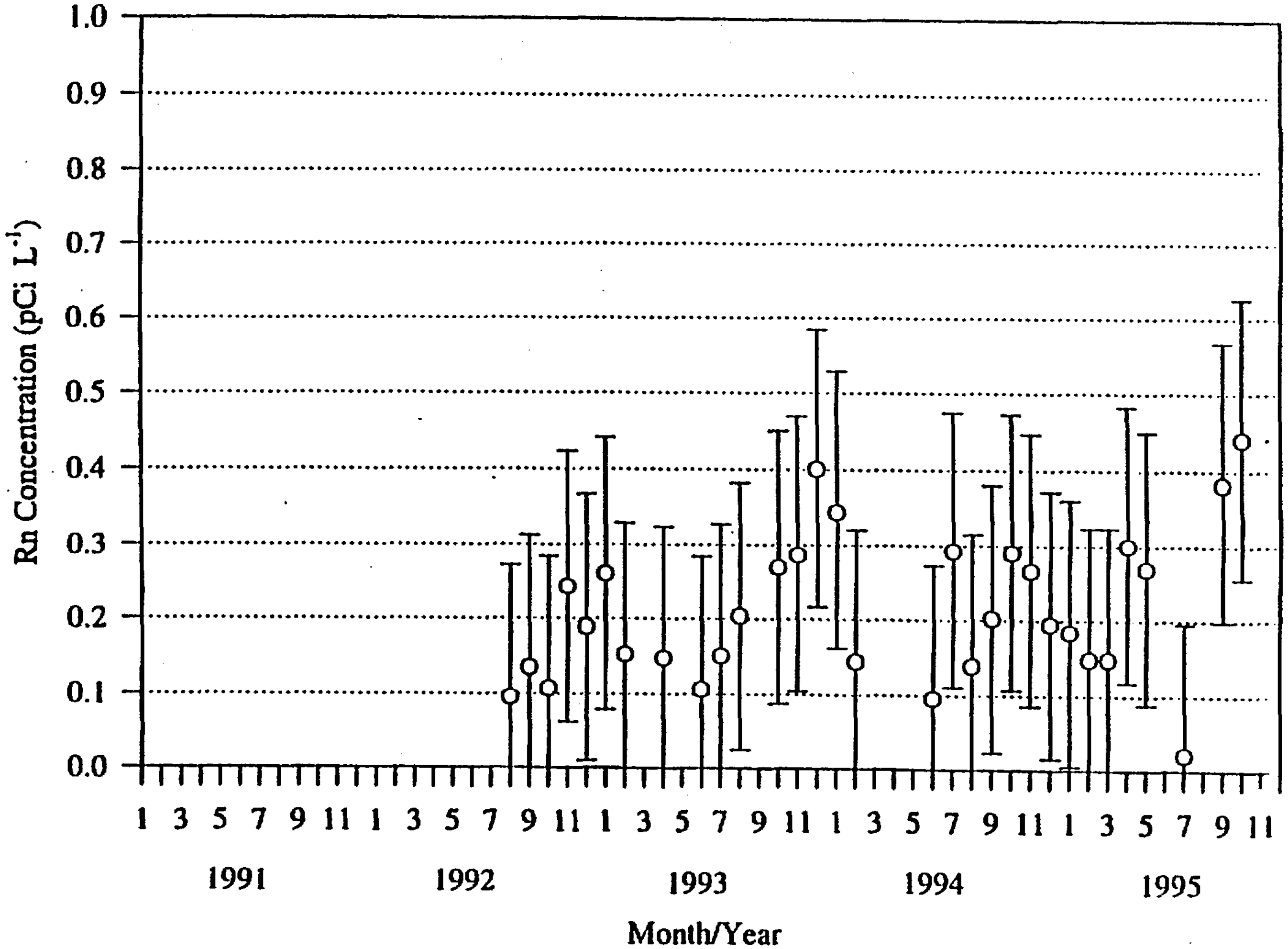
NOTE: Start date was 6/92.
Error Bars represent total measurement error.

Figure B-15. Monthly EIC radon concentrations at station NF95.



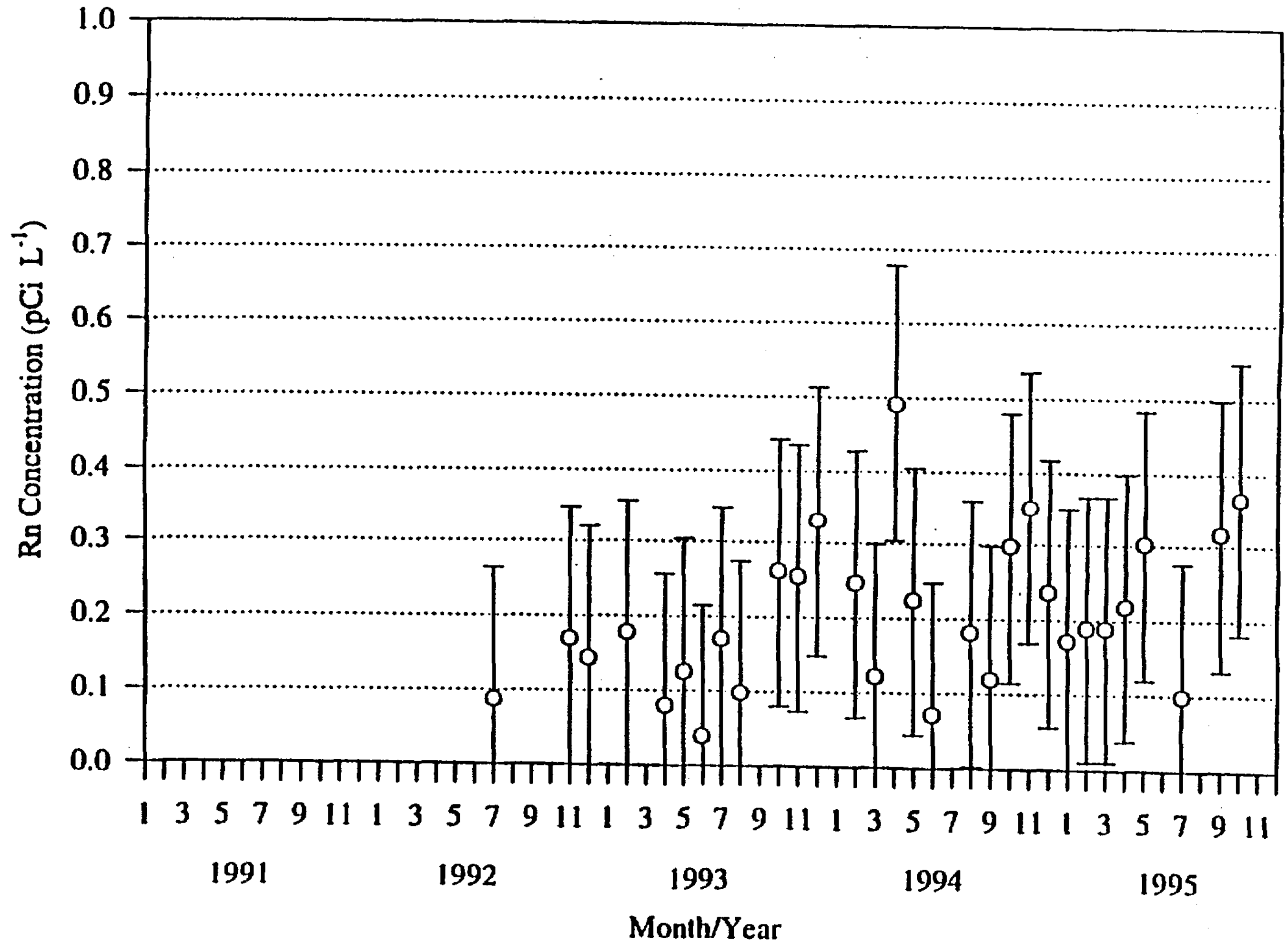
NOTE: Start date was 6/92.
Error Bars represent total measurement error.

Figure B-16. Monthly EIC radon concentrations at station NF98.



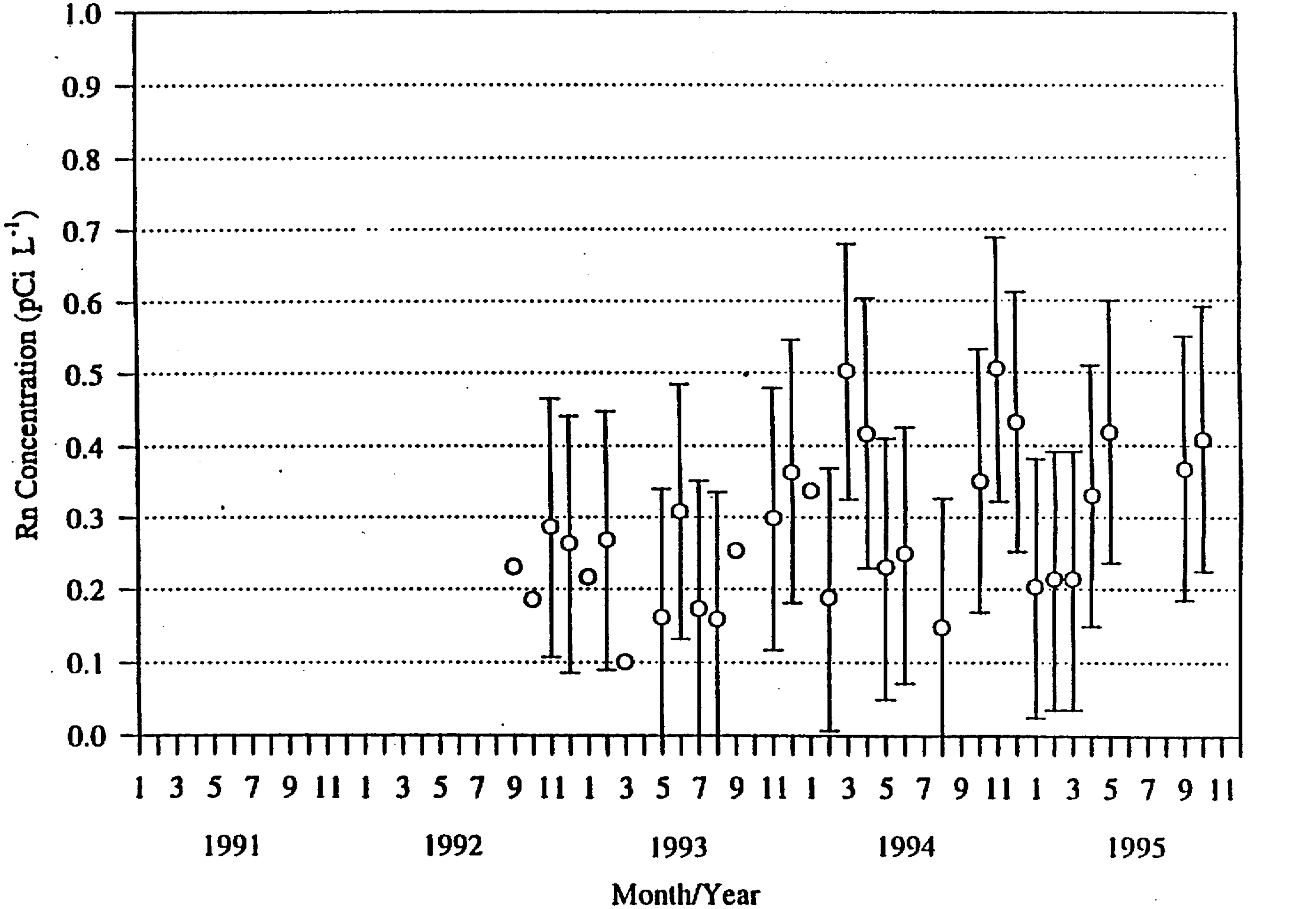
NOTE: Start date was 6/92.
Error Bars represent total measurement error.

Figure B-17. Monthly EIC radon concentrations at station NF99.



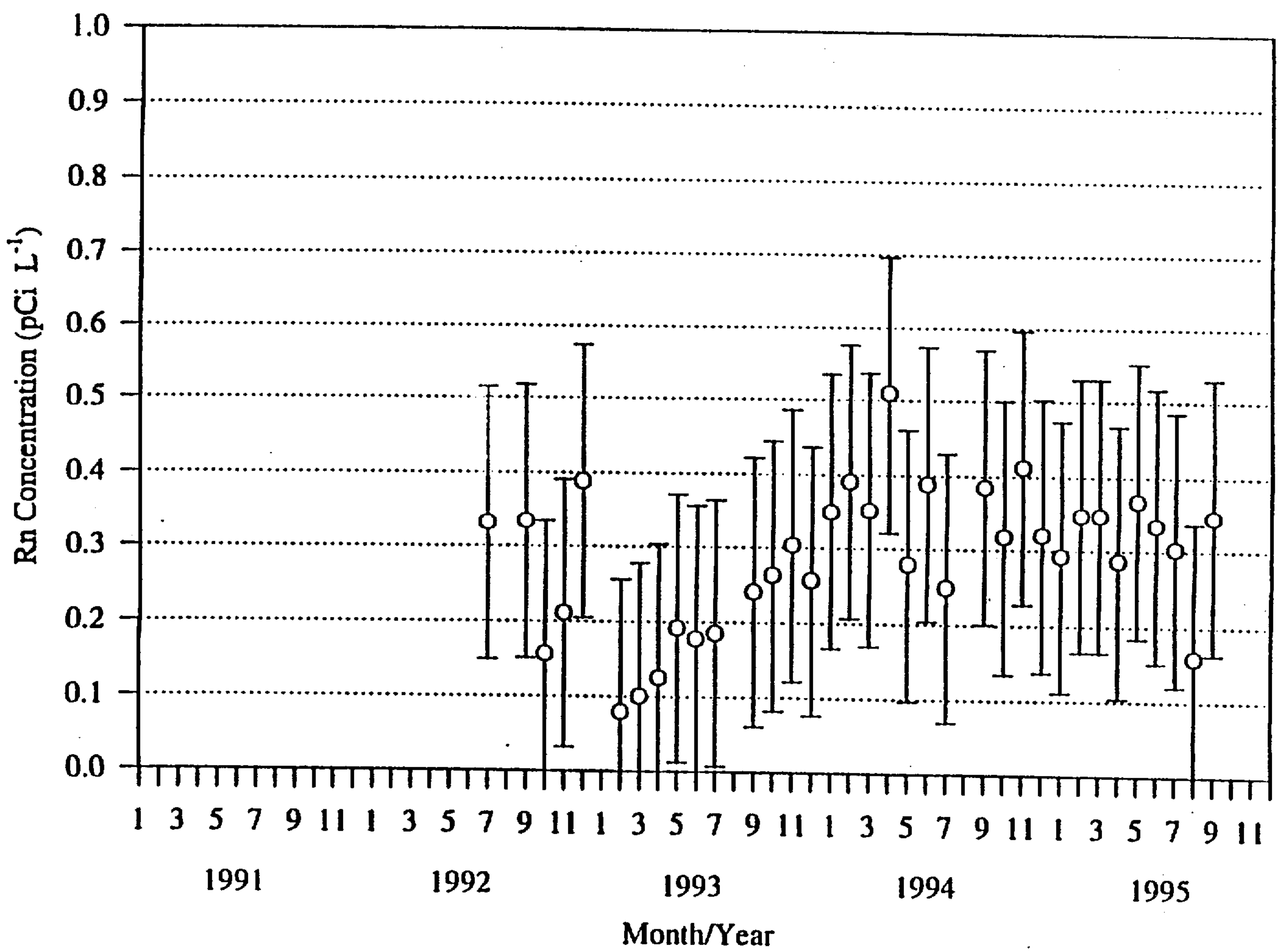
NOTE: *Start date was 6/92.*
Error Bars represent total measurement error.

Figure B-18. Monthly EIC radon concentrations at station NF100.



NOTE: Start date was 6/92.
Error Bars represent total measurement error.

Figure B-19. Monthly EIC radon concentrations at station NF101.



NOTE: Start date was 6/92.
Error Bars represent total measurement error.

Figure B-20. Monthly EIC radon concentrations at station NF102.

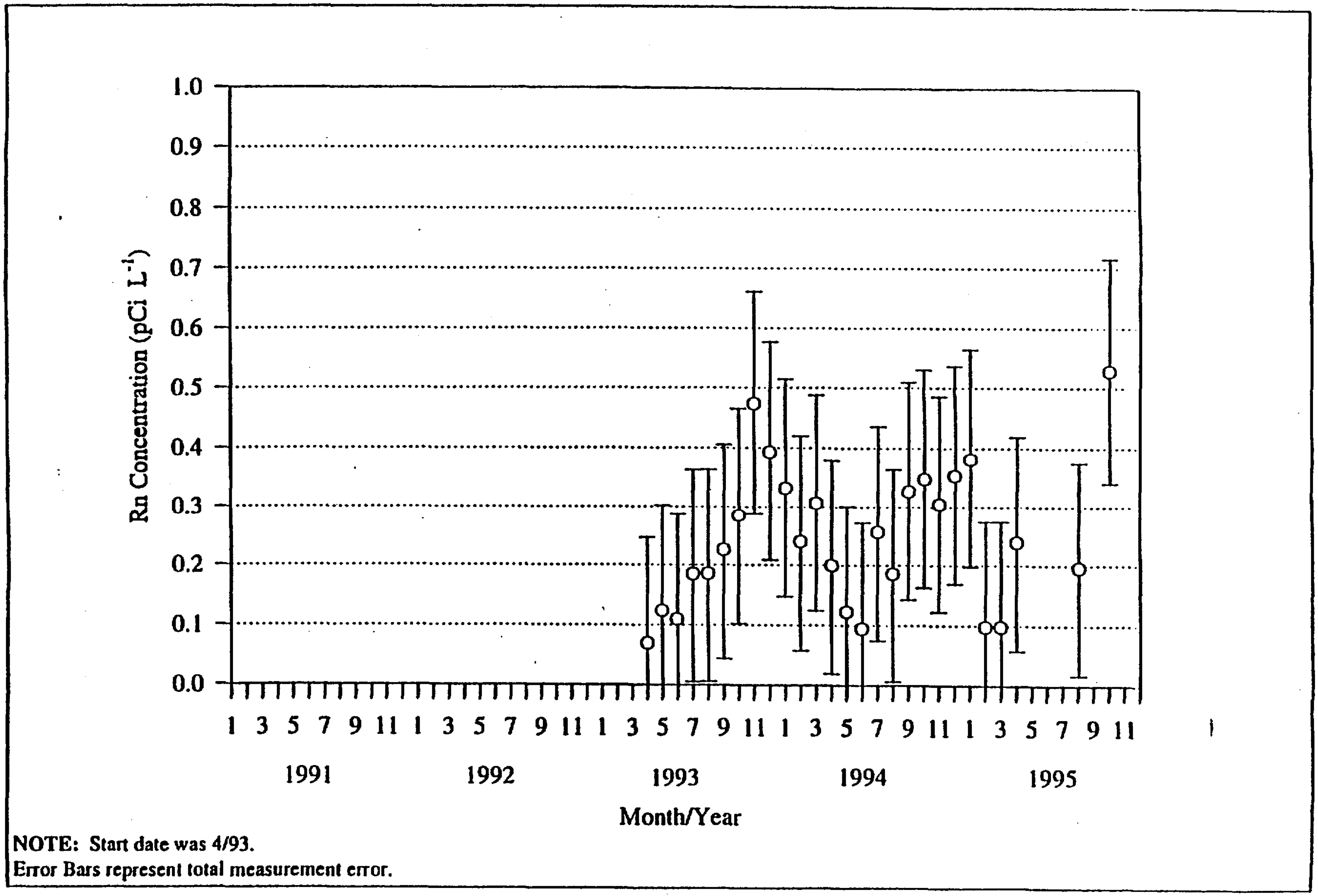


Figure B-21. Monthly EIC radon concentrations at station NF108.

APPENDIX C

QUALITY ASSURANCE

QUALITY ASSURANCE

Program management controls were applied to ensure a level of quality commensurate with regulatory requirements and industry standards. The validity of the data collected was ensured by qualified personnel implementing the requirements of specially developed procedures.

The conventional quality aspects of this program were monitored through an active audit and surveillance program to ensure proper quality assurance.

Controls to ensure data quality were initiated and maintained through the following practices:

- Documented personnel training and qualification prior to work
- Technical procedure review before approval for use
- Procedure compliance policy for work performance
- Regular calibration of the data collection instruments used for monitoring, sampling, analysis, and counting
- Mandatory documenting of nonconforming or deficient conditions potentially affecting data quality, together with a structured corrective-action process
- Appropriate data review prior to data reduction, analysis and reporting

Records management and document control were completed in compliance with appropriate procedures.

Methods used to review and validate EIC and CRM data prior to data analysis are discussed below. All data packages were reviewed and validated in accordance with approved R/EFPD procedures.

LIST OF ACRONYMS

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AGL	Above Ground Level
BP	Barometric Pressure
CF	Calibration Factor
CRM	Continuous Radon Monitor
CRWMS	Civilian Radioactive Waste Management System
CV	Coefficient of Variation
DOE	Department of Energy
EIC	Electret Ion Chamber
EF	Equilibrium Factor
ESF	Exploratory Studies Facility
FF	Far Field
HPIC	High Pressure Ionization Chamber
M&O	Management and Operating Contractor
NCRP	National Council on Radiation Protection and Measurements
NF	Near Field
NWPA	Nuclear Waste Policy Act
NWPAA	Nuclear Waste Policy Amendments Act
QA	Quality Assurance
R/EFPD	Radiological/Environmental Field Programs Department
SCPB	Site Characterization Plan Baseline

TRW	Thompson Ramo Woolridge
UNLV	University of Nevada, Las Vegas
WBS	Work Breakdown Structure
WL	Working Level
WLM	Working Level Month
YMP	Yucca Mountain Site Characterization Project

GLOSSARY

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Background radiation - Radiation in the environment from cosmic rays and naturally radioactive elements.

Curie (Ci) - A basic unit used to describe the rate of radioactive disintegration. One curie is equal to 37 billion disintegrations per second.

Data validation - A systematic process for reviewing a body of data against a set of criteria, to provide assurance that the data are adequate for their intended use.

Diurnal - Having a daily cycle.

Dose equivalent - The absorbed dose multiplied by the quality factor.

Effective dose equivalent - The summation of the products of the dose equivalent received by specified tissues of the body and the appropriate weighting factor.

Far-field sites - Monitoring stations more than 16 km from the Exploratory Studies Facility on the Yucca Mountain site.

Gamma ray - A photon or radiation quantum emitted spontaneously by a radioactive substance.
Ionization - The process of creating ions by adding or removing electrons from atoms or molecules.

Microroentgen (μR) - One-millionth of a roentgen.

Near-field sites - Monitoring stations within 16 km of the Exploratory Studies Facility on the Yucca Mountain site.

Picocurie (pCi) - One trillionth of a curie.

High Pressurized ion chamber (HPIC) - An instrument used to measure ambient gamma radiation by measuring the current produced when radiation ionizes gas in the chamber.

Primordial - Formed or present at the origin of the earth.

Radionuclide - An unstable isotope of an element that decays or disintegrates spontaneously, emitting radiation.

Radon progeny - Products of radioactive decay of Rn-222 gas.

Roentgen - The amount of gamma or X-rays required to produce ions carrying one electrostatic unit of electrical charge in one cubic centimeter of dry air under standard conditions.

Working Level - Any combination of short-lived radon daughter products in one liter of air that will result in the emission of 1.3×10^5 Mev of potential alpha energy.

Working Level Month - The cumulative exposure equivalent to exposure at one working level for a working month of 170 hours.

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REFERENCES

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